

MAY 1950

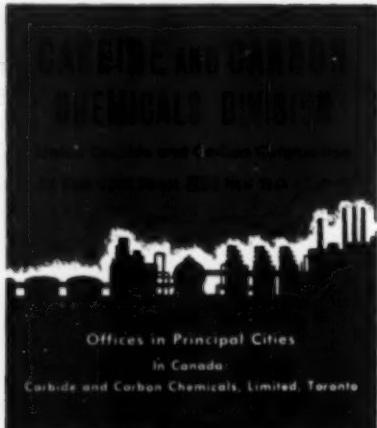
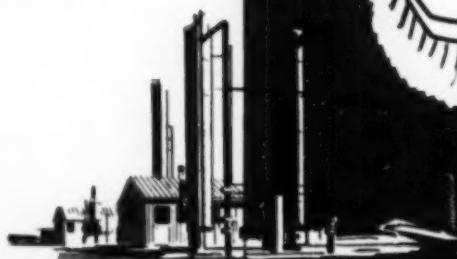
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By now, every member of the A.I.Ch.E. recognizes the above as the first of thirteen fits thrown by the Ichthyologists in honor of the Swampscott regional meeting, May 28-31. To the program already published in our March and April issues, the Boston Section has added three organized "bull sessions." They will cover "New fields for the Chemical Engineer," "Educating the Chemical Engineer for Industry," and "Liaison Between Research and Engineering." McCabe, Whitman, and Chilton, are the leaders of the sessions.

Read what the audience at the annual meeting in Pittsburgh thought of Licensing of Engineers—their expressions of opinion are contained in this issue, page 211.

Are you au courant on books in the chemical engineering field? Read our Marginal Notes. Herein experts in the specified fields judge new literature. Their reviews will save you valuable time and let you know whether or not you should invest your money in a particular work.

More on the latest literature covering equipment and chemicals in the process field can be found in this issue. To receive the full benefits use the Data Service Card following page 26.

Everybody likes a symposium—we are publishing another one in the June issue called "Training Engineers in Industry." Managements that have a program will see how to improve theirs, and those that have no training plan will want to initiate one after a reading of these opinions.

A message to company executives and personnel officers—when good chemical engineers are needed to fill the empty spots in your organization—use our classified section. The world's best chemical engineers belong to the American Institute of Chemical Engineers.

Volume 46

Number 5

# Chemical Engineering Progress

MAY

1950

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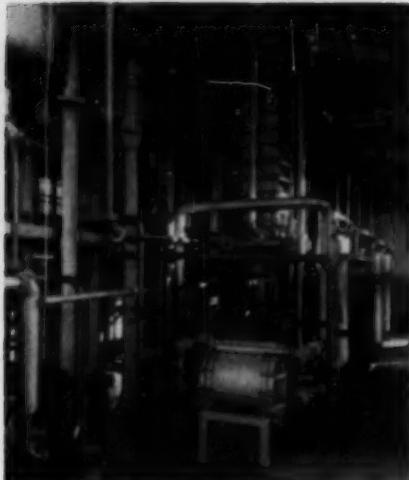
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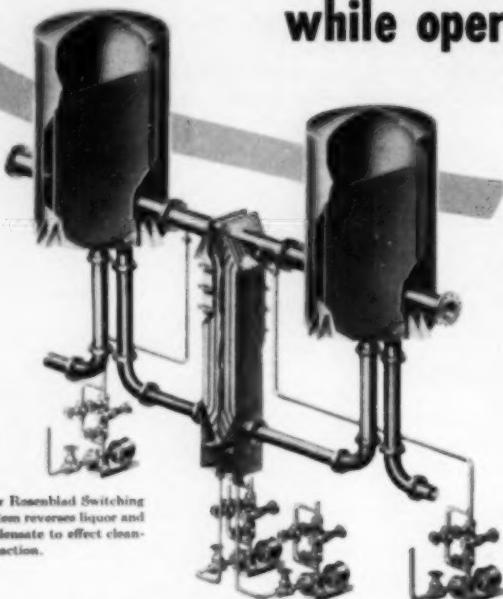
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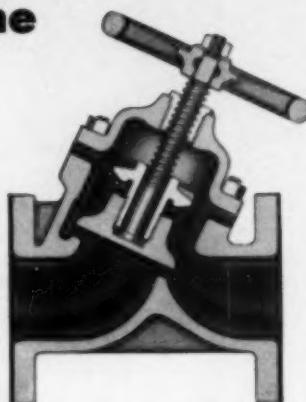
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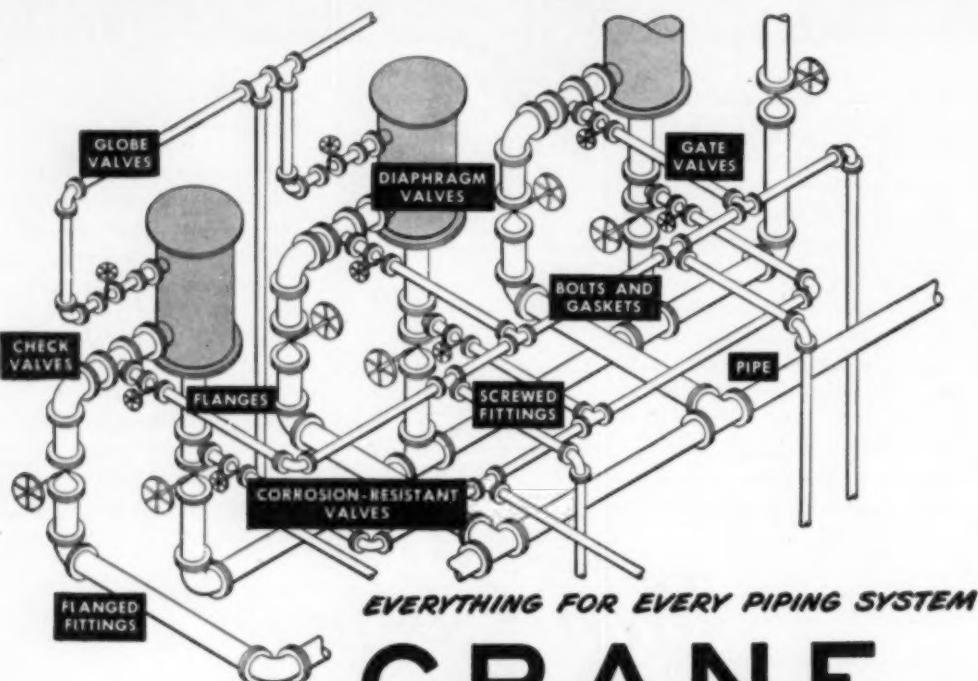
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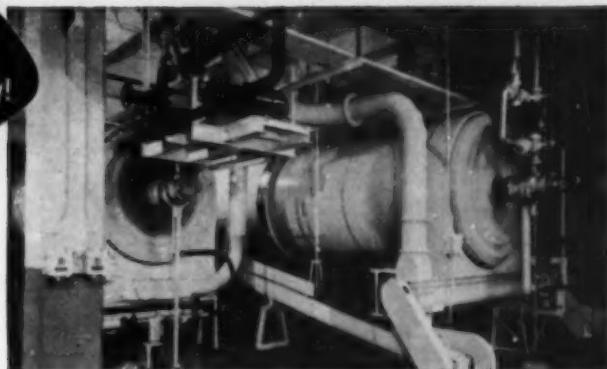
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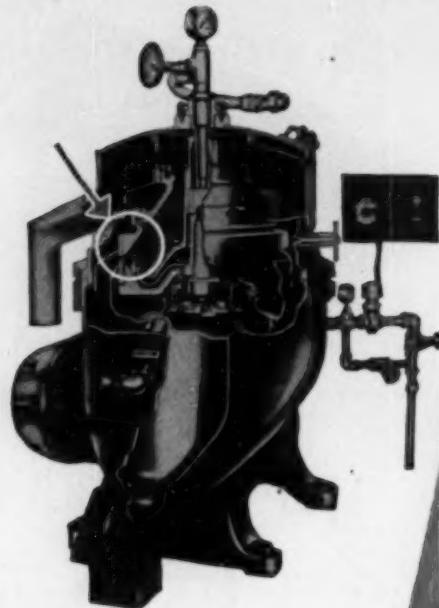
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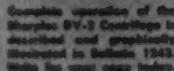
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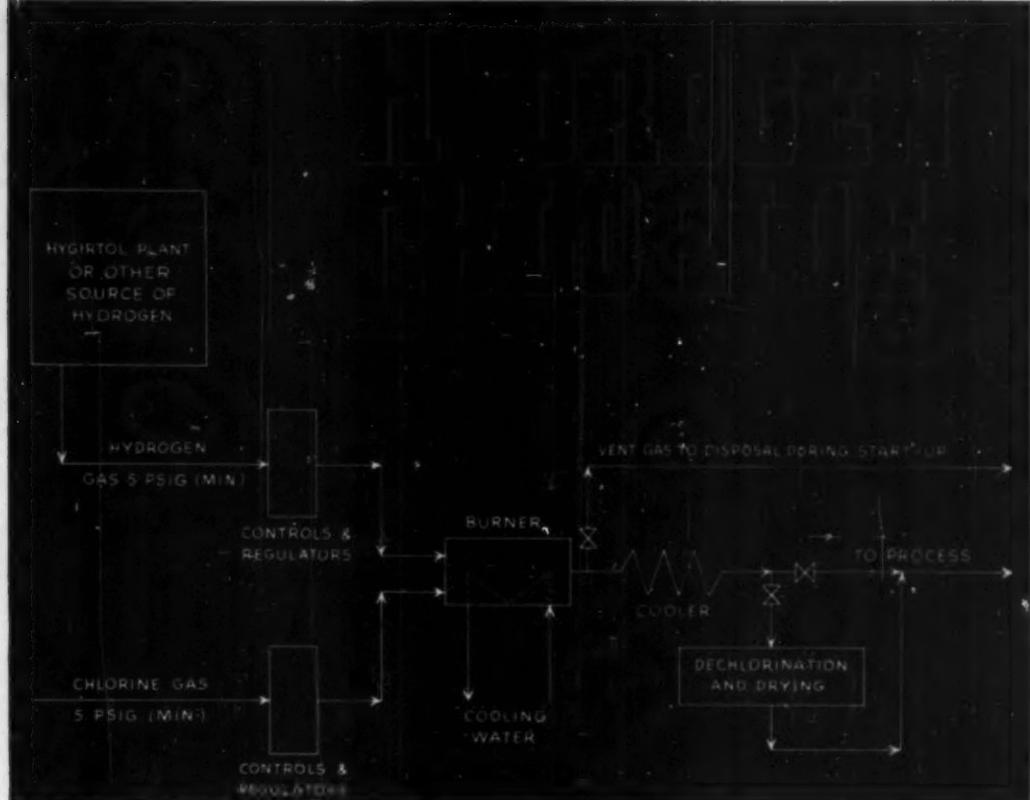
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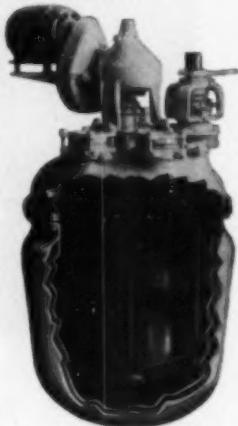
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# OPINION COMMENT

## WHAT MAKES FOR SUCCESS IN ENGINEERING?

THE desire for self-improvement, for success, is one of the great forces that drive humans. As a matter of fact, recognition of this underlies many sales promotion efforts, whether it is to Junior as an appeal to build up his muscles or sleek down his hair, or to his father offering him security via personal prophylaxis or courses in adult education.

Engineers too are concerned with the same problem. Sometimes, being engineers, they feel that something should be measured, some quantity must be specified so they may equate it for comparison. This results in questionnaires, polls, intelligence tests, and inventories of special skills.

On other occasions the engineers resort to the philosophical approach of confession, and exchange of experience. This results in symposia, lectures, bull sessions, and personal advice.

Each method tries to answer the same question—what must an engineer do to be successful in his profession?

We are not going to give our own personal evaluation of this question now, but rather explore two answers that have occupied our attention lately. The first answer was arrived at in the philosophical manner. Paul D. V. Manning, vice-president of International Minerals & Chemical Corp., was a panel member exploring the subject "What's New in Engineering Education" at a Father-and-Sons night at Northwestern Technological Institute. Dr. Manning, a director of the A.I.Ch.E., proposed list of ten qualities and attainments needed in our profession. Since they represent the qualified thought of an engineer who has spent his career in the chemical field, they deserve publicity and distribution. Here they are as he presented them.

1. A good knowledge of the fundamentals of science and the fundamentals of the branch of engineering in which he is working.
2. Absolute and uncompromising integrity in thought and action.
3. A well-developed ability to work with others and to make friends.
4. Good physical and mental health.
5. The ability to think, reason, analyze a problem and select its essentials.
6. A drive that makes him want to get things done, and done correctly.
7. A good memory.
8. A knowledge of how and where to find facts he needs but does not have.
9. A burning interest in his work that transcends the desire for money or personal gain, plus a pride in his profession.
10. The ability to use the tools of speech, economics, rapid reading, writing and English.

The list is a substantial, well-thought-out totting of specifications and one would be hard put to add to it. It is interesting though to compare this effort with qualities that were, in a fashion, measured. The measuring, true, was of opinion, but it offered enough alternatives so that it eliminated stray observations and prejudices. Specifically we refer to the pamphlet "The Most Desirable Personal Characteristics," published last year by the Engineers Council for Professional Development. The book (price twenty-five cents) reported an analysis of personal qualities in engineers most desired by executives, administrators, faculty members, personnel officers and college freshmen. For general engineering personnel the engineering executives want the following characteristics: first, intelligence, by which they meant clear thinking; second, dependability, by which was meant truthfulness; and organization acceptability, meaning cooperativeness was third.

The fourth attribute for engineers was to be dynamic, and three words,—effectiveness, confidence, and activity—were close in the executives' minds as descriptive of this particular quality. Emotional acceptability, or stability ranked fifth, and the sixth characteristic was physical acceptability, where cleanliness was the most desirable definition. Some rearrangement was manifest when other callings of the engineer were analyzed. For instance, for sales and distribution, the quality which received the highest rank for general engineering, intelligence, moved to fourth place in order of importance, and the quality of being dynamic moved to first place. Physical acceptability was second, emotional acceptability was third, dependability in fifth place, and organization acceptability in last place.

Naturally, opinion tends to be inconclusive in determining what a man needs for success. That there are measurable characteristics which have led some men on to positions of responsibility and others which keep men from such attainments, there can be no doubt. However, answers will probably never be found which will apply without fail. The qualities that make a man a success do not lend themselves to measurement, they are not capable of description. Something innate makes leaders, while circumstance at times merely makes for notoriety.

On occasion leaders in the field will break every rule in the book, and still maintain or attain leadership. Whether these are the exceptions, one has no way of telling, for the delicate balance of action and interaction between an individual and his working environment requires, in almost every case, individual judgment. Judging what is needed and accomplishing the end constitutes success. Only the average, the norm, can be measured, and if a particular situation is normal, measurement will aid. Those who succeed probably would have, no matter what the situation.

F. J. Van Antwerpen

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In the April issue Chemical Engineering Progress printed the contributed papers to the Licensing Symposium held at the annual meeting in Pittsburgh . . . this month, the audience present at the panel discussion speak their minds . . . is it licensing or registering? . . . advantages of joining national professional societies, the broader concept of ethics, enforcement, etc., are examined . . . here are thoughts to toy with and even to convert into action. . . .

# ENGINEERING LICENSING

## PRESENT STATUS AND FUTURE OUTLOOK

**E. W. Volkmann** (Koppers Co., Inc., Pittsburgh, Pa.): Our speakers gave us many reasons why the chemical engineer should become a licensed professional engineer, and they have pointed out the advantages of the engineer-in-training. Apparently, at least judging from Mr. Weiss' remarks, the status of the engineer-in-training has not been accepted with the expected eagerness by the younger members of the profession. On the other hand, I think it was Mr. Legaré who mentioned that down in the Carolinas as many as 90 per cent of the recent graduates have availed themselves of the opportunity of the engineer-in-training status.

In this connection I thought you might be interested in learning something about the figures for the State of Pennsylvania. I wrote to the Board of Registration and asked the Secretary for some statistical figures.

Before I read them to you I should mention, of course, that legislation in Pennsylvania was changed in 1945, when the new law of professional licensing was passed, to become effective in 1946. That gave the older members of the profession an opportunity to rush in and make use of the grandfather clause. Judging from the figures, a number of them did just that. Hence, 520 chemical engineers have become registered, without examinations since the new law was approved.

Now with regard to applications for certification of engineers-in-training: "Since the Act was approved on May 23, 1945," the Secretary writes, "24 chemical graduates applied for certificates, 21 of which have been granted." That would mean, on the average, only eight applications from graduates have been received per year.

Dr. Monrad estimates the number of chemical engineers graduating in the State of Pennsylvania each year at 400. This would indicate that only two percent thought it necessary to apply for certification as engineer-in-training. Personally, I think that is deplorable.

I would like to make one remark with respect to the attitude of Pennsylvania on accepting the registration of professional engineers of other states. I think it was mentioned that that was still difficult. In the letter I received from the Secretary, I have also the number of applications for examinations, and the number happens to be 28, 13 of which passed the examination and one was granted registration as he had passed the written examination given by the New York board. Apparently there are some exceptions to what you said.

**Z. G. Deutsch** (Consulting Engineer, New York, N. Y.): One of my committee jobs on Engineers' Council for Professional Development has been getting out a pamphlet for student guidance, and we wrote a little article for the high school student regarding licensing. The pamphlet was received by many professional men. Some of them changed the word "licensing" to "registration." At present I have cut out "licensing" wherever mentioned and substituted "registered" or "registering" or something of that sort. Which is preferred, and are the two terms interchangeable?

After that question is answered I would like to ask Dr. Fairman a question. What advantage is there to the rank-and-file practitioner in joining these various national societies?

**T. K. Legaré:** I will try to answer

whether it is "licensing" or "registration." Several years ago we voted on that and adopted "registration." Some of the men said, when you speak of licensing it reminds them of getting a license for a dog, a license to operate a hot-dog stand; it fails to distinguish this license from a business license. Some states do require a business license, all cities, I guess, require a business license. So we called this "legal registration," meaning that you have been registered legally, to show that you are legally qualified.

But lately many individuals and organizations have been using the term, "professional licensing." In New York State it is rather awkward because the New York Board and Department of Education do issue a license to a man and he is required to register that license in the county in which he is located. Several times we have written and asked if a man was registered, and if the answer was no, he was still issued a license by the New York authority to practice, but he is not registered.

Personally I prefer "registration" and if you read the Model Law you will find the word "license" doesn't appear anywhere in it. All the representatives of the national engineering societies that met several years ago to draft the Model Law agreed on the term "registration." I don't think you will find the term "license" in it.

**J. P. Fairman:** Dr. Deutsch's question is a difficult one to answer. I have been much disturbed—in the organizations that I belong to, by the efforts we make to sell people on the idea of membership. We get out elaborate pamphlets and we think up all the reasons why one will get something

immediate and specific out of joining our particular society. It seems to me that is one of the things we have done which has defeated our real objective of bringing about some better degree of professional consciousness.

Because the basic concept of a profession is a group of people who are rendering a service to society, the eyes of these people are on the idea of service, their objective is service, rather than immediate gain to themselves. I know that sounds like preaching. But it seems to me that that goes to the very heart of the matter.

There will be, in certain individual cases, immediate tangible benefits from registration, or immediate benefits to certain individuals from joining one or another society. I know that in the American Institute of Electrical Engineers, our Board of Examiners is all too frequently conscious of the fact that the application for admission or transfer is motivated by the profit motive, the engineer can get a better job, or thinks he can, if he has a higher grade of membership, or if he belongs to the organization. It seems to me we shouldn't promote that kind of thing.

That is a generalized answer to a specific question. But I have never been able, with good conscience, to make a clear answer on why I should join a society. My answer is, usually, you should go into it not for what you can get out of it but for what you can give to it, and as you give, your returns will be in proportion.

**Carleton C. Long** (St. Joseph Lead Co. of Pennsylvania, Monaca, Pa.): Professional registration is not any longer a theory, or a question of whether we should have it or not have it. It is here. The question really is, what are we going to do about it?

There is much that we as chemical engineers can do about it. The first thing is to interest ourselves in the administration of the registration acts in our various states; to interest ourselves in the operation of the county, state and national professional engineering organizations. It is a sad observation to make, but it is a fact that the majority of the competence of the profession is not represented by those presently registered.

Most engineers haven't wakened yet to the fact that we have something in licensing which has been thrust upon us, more or less from the outside. The profession is in the position now that Dean Holbrook was in 25 years ago. By and large, it doesn't like what it sees and it is inclined to shrug its shoulders about it. As long as the profession does that, the less competent and

less professionally inclined members of our engineering societies are going to run the thing.

As long as they who are less competent run things, they are not going to be run to the liking or advantage of the more competent, or, and which I believe is saying the same thing, to the advantage of the profession as a whole, and to the advantage of the public.

**D. O. Myatt** (Industrial & Engineering Chemistry, Washington, D. C.): I was very much interested in the case histories that were given revealing the incentives that led one of our speakers to decide he should become a legal engineer. The term, "legal engineer," suggests another thought, that so far as the practical, functional use of the license is concerned, it seems that the engineer is getting it primarily for the convenience of the lawyer and for the help of the lawyer. It also seems to me that it is not a present prerequisite that a person achieve legal status as an engineer before the professionally conscientious engineers can band together for the service functions. There are a number of organizations that purport to serve the profession, science, and society generally without asserting, at least in their organizational structure, that that service can be supplied only by legal engineers.

**J. F. Fairman:** I would assume that those remarks applied to me, and assume a rather sordid commercial concept on my part in getting a license.

No one had ever trained me to a wider concept. I was a member of my present institute ever since I was a student. I never heard anything about ethics. I heard nothing about registration. I heard a lot about how the engineer could get along better with people, how much better he could equip himself. The stress was always on the material side. When my eyes were opened, through the practical recognition that if I were registered I might get bigger and better plums, I was brought into professional contacts and met people for the first time in professional engineering who talked about these facts of life on—let's talk frankly about it—the spiritual side. I have endeavored to make good the deficiency in my own training, and endeavor to interest others in promoting engineering as a profession, not as a series of specialized occupations, important as these things are. I have tried to bring out the fact that there is another side if it is truly professional, that we work not solely for ourselves and our own immediate economic advantage, but we work to build a body of men to whom we can point with

pride as professional men, men dedicated to the service of the public. If they serve well, the economic rewards will take care of themselves. I have no doubt in my own mind that the problem of the young men could be solved if we would do right by them according to our opportunities, after they leave school and start on their first job by talking to them and counseling them, leading them, and saying what the faculty members ought to be saying.

The professors tell me, that when they say it, it's like water off a duck's back, but when a prophet from the outside says the same thing, the boys sit up and listen. So he may take it more seriously if we as professional engineers tell him these things.

This is the kind of thing we can do. And while I will confess I started from sordid motives, I realize that there is much more to it. We can not just let George do it. If we leave it to George, we'll not like what is done. If we are to have a democratic profession we have to do it ourselves. And we have now started, though we started late, really to use licensing as a tool for professional advancement. It is going to take a lot of us working together and not worrying too much about what we will get out of it. The greatest reward will be the satisfaction of helping some other member of our profession go on the right way toward professional advancement.

**Norman W. Franke** (Gulf Research and Development Co., Harmarville, Pa.): Is there any effort being made to unify registration laws? The state of Pennsylvania and the state of New York and each of the states have their own laws. Is there any way that we can get them together, so a man licensed in the state of Pennsylvania can operate somewhere else? We must realize that we don't have different countries to contend with, as they do in Europe, and many companies have men in more than one state.

**T. K. Legaré:** A great deal is being done about it. This Model Law I referred to was drafted several years ago and representatives of all the national societies attended these conferences. We drafted a new definition of the practice of engineering, and the National Council, consisting of membership of all the states and the three territories, is doing everything it can to get uniform laws.

What is needed is to have the laws amended through cooperation by the engineers. The members of the board can't do it by themselves, in fact some of them take the position they should

not even try, that the engineering profession in the state should promote the amendment of these laws.

I stated that 16 laws were amended last year to bring standards up to the Model Law. A great deal has been done along that line, but it is a slow process.

I think it is the duty of the engineering profession to do something to protect the title of "engineer." I often bump up against somebody who never has been to an engineering school, not even beyond high school, who puts up a big sign calling himself an engineer. I have a great collection of the uses of the title of "engineer." I have a photograph of a stand on Coney Island where in great big letters, it says "Hot Dog Engineer." I have a letter from exterminators in Chicago who call themselves "Exterminator Engineers." Then we have matrimonial engineers. We have people who call themselves floor engineers—they are experts on fixing floors but call themselves floor engineers.

That brings up the question of enforcement. It has been hard in some states to do much enforcing, some states have done a great deal. Ohio has done more than any other state, and that is because the State Society of Professional Engineers has gone to court.

In my particular state I have been a member and secretary of our Board for 27½ years. So far we have not had a case in court. But we have settled more than a thousand cases of improper use of the title "engineer," or practicing without being registered. I will give one specific case. A County Board in our state (the Chairman of the Board was a doctor) once elected the road foreman County Engineer.

I wrote this man that he couldn't use that title unless he came before the board and took an examination. He paid no attention to my letter. We thought we would have a test case and I notified him by a certain date we would make out a test case against him. The County Attorney then wrote me and said that this man did not claim to be an engineer, he was not doing any engineering work. The County Commissioners gave him that title, they were responsible for it, they thought it was a nice sounding title, and elected him County Engineer. I wrote and said I was glad to have that information, we would make the County Commissioners a part of the suit, we would make out the case against this individual and also against the County.

Then I got back another letter, asking what they could do about it. I told them that our South Carolina Board had no desire to embarrass this County Board,

that we would be glad to settle the case, and I made the suggestion that this man be called County Physician or County Attorney and it would be entirely satisfactory to us. The chairman was the County Physician, and the man who wrote me was the County Attorney. They caught the point, and sent me a telegram that they had had a meeting and the man was now County Superintendent of Roads.

**Wayne C. Edmister** (Carnegie Institute of Technology, Pittsburgh, Pa.): The majority of the members of American Institute of Chemical Engineers are of Junior grade.

Many men in the profession have been talking about Engineering Licensing idealistically, with which viewpoint one cannot quarrel. However, the younger men are thinking of things from the economic point of view. They want to know how they are going to get a job and make enough money to get married or buy a home or raise children, and pay the grocery bill. In order to interest these younger people we have to talk their language.

It's all right to talk idealistically and tell them they will benefit by running their profession themselves rather than letting other people run it, but I believe from the standpoint of the younger engineers you have to talk economics as well. I don't like the idea of pooh-poohing the dollars-and-cents part of it. That is why men study engineering—to make a living. Most of them are employed by the larger companies, chemical companies, engineering companies and oil companies, where I presume it is not a requirement for the job.

I suggest that we be more realistic; the younger chemical engineers are primarily interested in how licensing will improve their income.

**E. A. Holbrook:** It is perfectly true that there are hundreds and thousands of engineers employed by corporations, on detailed work or on specific work, where the man doing that work is not required to be a professional engineer. But somewhere in that organization today, either in Pennsylvania or in New York, is a man who puts his stamp of approval on the work as a professional engineer. Under the law if you design engineering work, let it be a pressure vessel, where the health and safety of the public are at stake, and that pressure vessel breaks, I wouldn't like to think of the consequences if the designer of the pressure vessel was not per se a registered engineer.

So that, if a young man is looking for success, advancement, a lifetime in the profession, the earlier he gets his reg-

istration I think the better. Although in the dollars-and-cents sense he may not use it for a year or two it is certainly a lot easier to get it six or eight years out of school than it is 30 or 40 years after he gets out of school.

**J. F. Fairman:** I did suggest that those of us who are bosses could do something practical about it in our own organization. Perhaps I didn't expand that point enough. I believe idealism should be put into practice. And we have done that in our own company for the last few years. We have stopped using the title, "engineering," in any form for people who are not in fact engineers. And we have therefore raised the price tag on those titles to a value which is commensurate with the training and experience of an individual who in fact is an engineer.

As a matter of fact, that doesn't inflate your payroll appreciably. In any large industrial organization, whether it is a public utility or a manufacturer or whatnot, your payroll is the great rank and file who in this day and age are definitely unionized. What you do for the relatively few professional people on your payroll is not going to make or break the corporation. So I say it is up to us who are leaders in the profession, who are employers of younger engineers, to treat those fellows as we believe they should be treated, according to their training and education and age and competence. And we can do it—we are the only people who can do it. And when we start to do that a lot of these problems of the young engineer will evaporate into thin air.

Yes, I am idealistic, but I am also practical, and I believe we idealists need to put our idealism into practice, and I am sure it doesn't cost us much, relatively.

Now as to the point of view of the young man who has the economic problem of the \$25. And I will grant that is a problem of considerable magnitude. It seems to me that we can show him rather convincingly that in spite of the fact that it looks like a large sum of money in one chunk to get his license, and in spite of the fact that the actual dues in some one or more professional societies look like a considerable sum of money, yet compared to what he has already invested in his preparation to enter this profession, it is a drop in the bucket.

And as engineers, we are supposed to have some economic sense. Well, now, which does us the most good in the long run? I mean "us" individually? The answer is our contact with our colleagues in an organization such as this where, by the exchange of technical in-

formation through publications and discussion, each gains something. An engineer is entitled to that gain by paying his relatively modest dues to be a member. We need those technical contacts, we need that opportunity to grow in our particular technology.

But many of us are coming to think that we need to recognize the broader sphere of common interest which we have, regardless of our particular branch of specialization, and work together to build a profession, feeling confident that when we build something that is recognized as a learned profession, such as medicine and law, the rewards will come. I think that is practical idealism and I think we can sell it to the young men.

**M. H. Chetnick** (University of North Dakota, Grand Forks, N. D.): Several years ago I was invited to attend a state meeting of professional engineers. I was much surprised to find that a small majority of the membership consisted of professional men, that is, mechanical, chemical, or civil engineers. The majority seemed to be men who worked in the State Highway Department, surveyors, contractors, and others. I wondered just how many of those men were qualified to join their national society and how many had engineering degrees.

I wonder if any statistics are available on what percentage of men who are licensed actually have engineering degrees and are members of their national society.

**J. F. Fairman:** I haven't the statistics at my fingertips. I will admit that my feeling the first time I attended a professional engineers' meeting, my reaction was somewhat like the last speaker's.

When you pass a licensing law you can't deprive a man from making his living, and so you have the grandfather clause, which registers a man providing he can show that he has been doing such and such for X number of years. Time will cure that. The doctors had it. In my early days we had doctors who had learned medicine by associating with somebody, who associated with somebody, who in turn associated with somebody, and it went back to the dim dark past. We also had some young men who had real training and they were the ones we went to if we were really ill.

**Anonymous:** I happen to be a registered engineer in the State of Ohio. Of course, that doesn't permit one to practice in the state of Pennsylvania. I do happen to be general manager of a

plant in Pennsylvania and it would be to our advantage to have a registered engineer. I have no great desire to take a lot of examinations.

So my problem is to try to convince some of the younger fellows that they should obtain a license. I have approached four or five of them, and they give me an argument that the fellows they see who are registered could not pass these examinations. How should I answer them?

**T. K. Legaré:** I would like to say to our friend, don't be too hard on some of the fellows who are not college graduates. We recently had a written examination for, I think it was five mechanical engineers, and the questions were prepared by the professor of mechanical engineering. Those papers were numbered, and only I knew which was which. The professors came in, very much excited, and said one of the boys got 97 per cent, "And I want to know if it was one of mine." The man who made the 97 had never been through high school.

Regarding benefits to the younger engineers, several companies require their men to be registered.

Our State Board of Health has a schedule of salaries and the man who wants to be put in that schedule as Sanitary Engineer has to be registered. If he is not he is called a sanitarian, or something like that, and makes about a hundred dollars a month less.

**John J. O'Neill** (Western Cartridge Co., Division of Olin Industries, East Alton, Ill.): To reiterate a point made previously, the fact that only 24 chemical engineers have seen fit to apply for registration in the State of Pennsylvania, in the last three years, points out a serious fault in my mind, not so much as far as regulation of engineers is concerned but a fault which the American Institute of Chemical Engineers and all other engineering institutes are facing; and that is education of the engineer.

I am not blaming the colleges—because in my estimation the education of an engineer is only beginning when he gets his Bachelor's degree. But unfortunately too often it is not only the beginning but also the end and what he gets from then on is what he gets on his own. That brings us back to professional guidance. In my estimation professional guidance as it is now practiced is neither fish, flesh, nor good red herring—it's nothing.

The only step forward that I have seen in the last couple of years to advance professional guidance, was made by Dr. P. D. V. Manning about three months ago. He suggested in

*Chemical Engineering Progress* that the engineers of two- or three-years' experience go back to the colleges and talk to the seniors before they receive their degrees, telling them a little bit about what the engineering profession really is. I think that's fine. I think that ought to be done, I am trying to practice that myself.

I think this suggestion has to be picked up in industry, and we can't just accept the young engineer and let it go at that; if he joins the A.I.Ch.E. fine; if he doesn't, fine, if he becomes a registered professional engineer fine, and if he doesn't, fine. I think we have to decide what is the best course and actually guide the young engineers in the first three or four years after they receive their B.S. degree.

**Charles R. Bartels** (E. R. Squibb & Sons, New Brunswick, N. J.): I am a professional engineer from the state of New Jersey.

Licensing or registration implies qualification. After a man is qualified he has perhaps specialized in one small part of the engineering field. Yet by virtue of his registration or licensing he can put his seal on any one of a large number of papers, designs, plans, blueprints, which indicate to the non-professional observer that these are satisfactory. There is, of course, the matter of ethics involved. Some people take that with less responsibility than others. However, the point is there, a man can specialize, and yet by virtue of his engineering license can approve work which is almost wholly outside his field of knowledge.

**J. M. Weiss:** As far as that is concerned there has been no trouble in New York State; there hasn't been a case yet. Such things are handled by ethics, and they can revoke a license if a man attempts to go into a field in which he is not qualified. That has not happened. I think you have the same thing that you have in the medical profession. Whether a man is a surgeon or an eye specialist or a heart specialist, he is first of all a doctor, and you have to rely on his professional ethics and professional feeling to prevent his practicing in a field in which he is not competent. When our profession is high enough in standing there is no trouble from that.

And it has been rather heartening that in New York—and in New Jersey, where there is that situation that the speaker has mentioned—there hasn't been a case yet of any complaint of an engineer going out of the sphere in which he is qualified.

THE END

# BATCH RECTIFICATION

## Analytical Expressions for Yield Fraction of Batch Distillation with Finite Reflux Ratio

JU CHIN CHU

Polytechnic Institute of Brooklyn, Brooklyn, New York

With the application of Smoker's equation and Eshaya's method respectively, analytical expressions are derived for binary mixtures giving the yield of distillate of a given composition obtainable by batch fractionation of a given charge in both an ideal column and a column with holdup. It is assumed that the reflux ratio is continuously increased throughout the rectification to maintain the product composition constant with a finite reflux ratio at the cutting point. The equations derived are applicable to complex mixtures if the effective binary system as proposed by Hengstebeck is employed.

METHODS of calculating batch fractionation curves for a binary mixture, where the effect of column holdup is recognized, have been given by Rose, Welshans, and Long (10) and Colburn and Stearns (4). In both cases a constant reflux ratio is assumed and the composition of the overhead product varies accordingly.

Edgeworth-Johnstone (5) pointed out the fact that batch fractionation in practice, starts with a low reflux ratio and increases as the cutting point is approached in order to conserve heat used in fractionation. Composition of the distillate is maintained approximately constant at the desired value throughout the distillation. By assuming that the reflux ratio is continuously increased throughout the distillation to maintain a constant composition of the distillate and becomes infinity at the cutting point, he (5) derived equations for both binary and complex mixtures showing the yield of distillate of given composition obtainable by batch rectification of a given charge, taking into account both degree of fractionation and column holdup. Equations, derived from the material balance and Fenske's equation for total reflux (8), are exact for binary mixture and of a good approximation for complex mixtures.

Bogart (1) carried out a number of McCabe and Thiele constructions at different reflux ratios, keeping the dis-

tillate composition constant, and plotted composition of liquid left behind in the still against a function of composition changes and reflux ratio. However, no column holdup has been allowed in his derivation.

Edgeworth-Johnstone (6) described a general method for calculating yields from batch rectification of a binary mixture under constant distillate condition for any given reflux ratio at the cutting point. The method allowed for the effect of column holdup. However, his stepwise method is tedious. With the aid of Underwood's equation for calculating minimum reflux ratio (13), he derived an approximate analytical expression for both binary and complex mixtures, applicable to the cases where holdup is negligible and  $a^{n+1}$  is greater than 5000.

Analytical expressions are developed here which give the yield from batch rectification directly when reflux ratio is continuously increased throughout the rectification to maintain the product composition constant, and has a finite value at the cutting point.

This was described as "batch rectification under constant distillate condition" (4). To secure this constant distillate composition, a constant rate of heat input to the still and an automatic control of reflux ratio with the temperature of overhead vapor are provided. Through the use of an "effective binary

system" as introduced by Hengstebeck (9), the derived equation can be used also for solving problems in batchwise multiple component rectification.

### Binary System

Due to the presence of holdup of liquid in the column and incomplete fractionation, the actual yield of distillate can never reach 100%. Packed columns usually have lower holdup than the plate column with the same number of theoretical plates. The channeling effect present in a packed column limits the possible increase in its height for a difficult separation. Redistribution devices after every few feet are frequently used to minimize channeling in industrial installations. With large relative volatility of the components involved in batch fractionation, a packed column with a relatively fewer number of theoretical plates and low holdup gives better yields than a plate column with many plates which inherently carry a much higher holdup.

### Ideal Column

*1. Application of Smoker's Equation.* Consider an ideal column having  $n$  theoretical plates with no holdup. A batch of  $F$  moles of a binary mixture, in which the mole fraction of the more volatile component is  $x_B$ , is distilled with increasing reflux ratio to maintain the distillate composition constant at  $x_D$ .

From a material balance up to the cutting point of the batch distillation when a distillate of constant composition has been collected:

$$F = L + D \quad (1)$$

$$Fx_D = Lx_B + Dx_D \quad (2)$$

Solving (1) and (2),

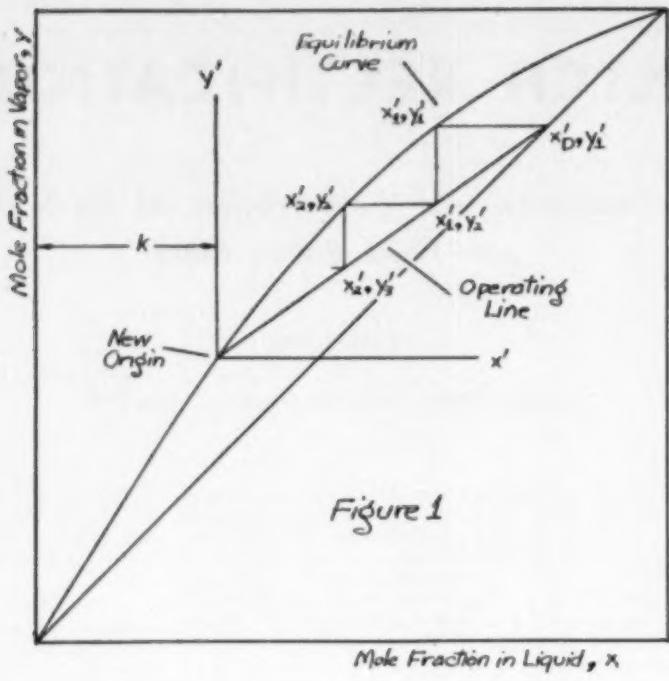


Figure 1

Mole Fraction in Liquid,  $x$

$$D = \frac{F(x_B - x_f)}{x_B - x_D} \quad (3)$$

With a translation of coordinate axes so that the origin is located at the point of intersection of the operating line and the equilibrium curve, Smoker (12) developed an ingenious method for an analytic determination of number of theoretical plates in a fractionating column for a binary system.

If the equation of the operating line and the equilibrium curve are, respectively,

$$y = mx + b \quad (4)$$

$$y = \frac{ax}{1 + (a-1)x} \quad (5)$$

They became, when referred to the new axes,

$$y' = m'x' \quad (6)$$

$$y' = \frac{ax'}{c^2 + c(a-1)x'} \quad (7)$$

Where

$$c = 1 + (a-1)k$$

$k$  is the  $x$  coordinate of the new origin and is readily obtained either by solution of the quadratic equation resulting from the elimination of  $y$  between Equations (4) and (5), or preferably by using a monograph prepared by Bisesi (2).

Starting the stepwise procedure from the point  $x_D', y_1'$  on the operating line (See Fig. 1) which is the composition of the vapor leaving the top plate, use of a total condenser is assumed. Composition of the liquid from that plate is given by the equation of the equilibrium curve.

$$x_1' = \frac{c^2 y_1'}{a - c(a-1)y_1'} \quad (8)$$

Substitute (6) into (8),

$$x_1' = \frac{mc^2 x_B'}{a - mc(a-1)x_D'} \quad (9)$$

Similarly,

$$x_2' = \frac{mc^2 x_1'}{a - mc(a-1)x_1'} \quad (10)$$

Combining (9) and (10),

$$x_2' = \frac{mc^2 c^4 x_D'}{a^2 - mc(a-1)(a+mc^2)x_D'} \quad (11)$$

Continuing the stepwise substitution to the  $n$ th plate and solving for the num-

ber of theoretical plates:

$$n = \frac{\log \left[ \frac{x_D'(1-Mx_n')}{x_n'(1-Mx_D')} \right]}{\log \left( \frac{a}{mc^2} \right)} \quad (12)$$

Where

$$M = \frac{mc(a-1)}{a-mc^2}$$

Carrying the stepwise substitution one step further,

$$n+1 = \frac{\log \left[ \frac{x_D'(1-Mx_B')}{x_B'(1-Mx_D')} \right]}{\log \left( \frac{a}{mc^2} \right)} \quad (13)$$

Solving (13) for  $x_B'$ ,

$$x_B' = \frac{x_D'}{(1-Mx_D') \left( \frac{a}{mc^2} \right)^{n+1} + Mx_D'} \quad (14)$$

Since

$$x_D' = x_D - k, x_B' = x_B - k$$

(14) can be reduced to

$$x_B = k + \frac{x_D - k}{[1 - M(x_D - k)] \left( \frac{a}{mc^2} \right)^{n+1} + M(x_D - k)} \quad (15)$$

It is noted that Equation (15) expresses the composition of the liquid left in the still at the end of batch rectification in terms of a function containing the constant composition of overhead, average relative volatility of the system, reflux ratio at the end of batch rectification and the number of theoretical plates in the column. Therefore, use of Equation (15) avoids the tedious plate-to-plate calculation in finding the composition of the liquid left in the still at the end of batch distillation.

Substituting (15) into (3)

$$D = \frac{F \left[ k + \frac{x_D - k}{[1 - M(x_B - k)] \left( \frac{a}{mc^2} \right)^{n+1} + M(x_B - k)} - x_f \right]}{k + \frac{x_D - k}{[1 - M(x_B - k)] \left( \frac{a}{mc^2} \right)^{n+1} + M(x_B - k)} - x_D} \quad (16)$$

The total quantity of distillate of composition  $x$  contained in the original charge is  $Fx_f/x_D$ . Dividing the amount of distillate collected up to the cutting point by this quantity gives the yield fraction:

$$Y = \frac{D}{Fx_f/x_D} = \frac{x_D}{x_f(k - x_D)} \frac{(k - x_f)U + x_D - k}{U - 1} \quad (17)$$

Where

$$U = [1 - M(x_B - k)] \left( \frac{a}{mc^2} \right)^{n+1} + M(x_B - k)$$

Equation (17) indicates that the yield fraction of a binary batch rectification can be calculated if the composition of the original charge into the still, reflux ratio at the end of the distillation, composition of the overhead product desired, average relative volatility of the system, and the number of theoretical plates in the column are given.

*2. Application of Eshaya's Method.* Eshaya (7) introduced an equivalent straight line, which is defined as "fictitious equilibrium line," in place of the equilibrium curve on McCabe-Thiele's diagram. Equations of the fictitious equilibrium line and the operating line are:

$$y = m_1 x + b \quad (18)$$

$$y = mx + b \quad (19)$$

Starting from the top of the column the stepwise substitution by means of (18) and (19) gives:

$$n = \frac{\log \frac{x_D}{x_n}}{\log \frac{m_1}{m}} \quad (20)$$

or

$$x_n = \frac{x_D}{\left( \frac{m_1}{m} \right)^n} \quad (21)$$

Where  $n$  = number of theoretical plates in the fractionating column.

Carry the stepwise substitution one stage farther,

$$m_1 = a + \frac{1}{x_D + x_f} \left[ -\frac{a_B}{2} (x_D^2 - x_f^2) + \frac{a_B^2}{3} (x_D^3 - x_f^3) \right. \\ \left. + \dots - \frac{a_B^{n-1}}{n} (x_D^n - x_f^n) - 2.303x_B(1-m) \log \frac{x_D}{x_f} \right] \quad (22)$$

Where  $B = a - 1$ .

When only the first three terms of the expansion are considered sufficient, Equation (26) can be simplified to

$$m_1 = a - \frac{aB}{2} (x_D + x_f) \\ + \frac{aB^2}{3} (x_D^2 + x_D x_f + x_f^2) \\ - \frac{2.303x_B(1-m)}{x_D - x_f} \log \frac{x_D}{x_f} \quad (28)$$

(22) can be solved for  $x_B$ :

$$x_B = \left( \frac{m}{m_1} \right)^{n+1} x_B \quad (29)$$

Substituting (29) into (3),

$$D = \frac{F \left[ \left( \frac{m}{m_1} \right)^{n+1} x_B - x_f \right]}{\left( \frac{m}{m_1} \right)^{n+1} x_B - x_D} \quad (30)$$

The yield fraction can, therefore, be expressed by:

$$a \int_{x_n}^{x_D} \frac{dx}{1 + (a-1)x} - m_1 \int_{x_n}^{x_D} dx - b \int_{x_n}^{x_D} \frac{dx}{x} = 0 \quad (24)$$

After integration and substitution of limits, Equation (24) can be solved for  $m_1$  (3):

$$m_1 = \frac{\ln \left[ \frac{1 + (a-1)x_D}{1 + (a-1)x_n} \right] \frac{a}{a-1} \left[ \frac{x_n}{x_D} \right]^b}{x_D - x_n} \quad (25)$$

Where  $x_n$ , the composition of liquid from a plate above the still, is related to the composition of liquid in the still by

$$\frac{ax_B}{1 + (a-1)x_B} = y_B = mx_n + b$$

or

$$x_n = \left[ \frac{ax_B}{1 + (a-1)x_B} - b \right] \frac{1}{m} \quad (26)$$

It was noted that the final form of Equation (31) for the calculation of the yield fraction is simpler than that derived from Smoker's equations. However, the slope of fictitious equilibrium line can not be found directly from Equation (25) and (26), as  $x_B$ , the still composition at the cutting point is also unknown. A trial-error method has to be used in solving Equations (25),

(26), and (29) for the slope of the fictitious equilibrium line at the cutting point.

#### Column with Holdup

**1. Application of Smoker's Equation.** Considering an actual column having a holdup of  $Q$  moles per theoretical plate with other conditions the same as for the ideal column, at the beginning of distillation the column is assumed to be empty. If  $Qx$  represents the total moles of  $A$  holdup in the column, the material balance equations become:

$$F - nQ = D + L \quad (32)$$

$$Dx_D + Lx_B = Fx_f - Qx \quad (33)$$

Where  $\Sigma x$  represents the summation of mole fractions of more volatile component in the liquid on plates.

Solving (32) and (33) for  $D$ ,

$$D = \frac{Fx_f - Q\Sigma x - Fx_B + nQx_B}{x_D - x_B} \quad (34)$$

By substituting (15) into (32),  $x_B$  can be eliminated,

$$D = \frac{Fx_f - Q\Sigma x - (F - nQ) \left[ k + \frac{x_D - k}{U} \right]}{x_D - k - \frac{x_D - k}{U}} \quad (35)$$

Dividing  $D$  by  $\frac{Fx_f}{x_B}$  one obtains,

$$\text{Yield fraction } Y = \frac{Dx_D}{Fx_f} = \frac{x_D}{Fx_f} \left\{ \frac{Fx_f - Q\Sigma x - (F - nQ) \left[ k + \frac{x_D - k}{U} \right]}{(x_D - k) \left( 1 - \frac{1}{U} \right)} \right\} \quad (36)$$

The proportion of vapor in the column is assumed to be so small that the average composition of the total material holdup is almost the same as that of liquid holdup.

Composition of the liquid from the top plate of the column is given by

$$x_1' = \frac{mc^2 x_D'}{a - mc(a-1)x_D'} \quad (9)$$

By the stepwise substitution of equilibrium curve and operating line, Smoker (12) gave the expression for the composition of the liquid from the  $n$ th plate. Referring to his proposed new origin:

$$x_n' = \frac{m^n c^{2n} x_D'}{a^n - mc(a-1) \frac{a^n - m^n c^{2n}}{a - mc^2} x_D'} \quad (37)$$

Composition of the liquid from  $n$ th plate is therefore represented by:

$$x_n = k + x_n' = k + \frac{m^n c^{2n} x_D'}{a^n - mc(a-1) \frac{a^n - m^n c^{2n}}{a - mc^2} x_D'} \\ = k + \frac{m^n c^{2n} (x_D - k)}{a^n - mc(a-1) \frac{a^n - m^n c^{2n}}{a - mc^2} (x_D - k)}$$

Hence,

$$\Sigma x = x_1 + x_2 + \dots + x_n \\ = \sum_{n=1}^{\infty} x_n = nk + \sum_{n=1}^{\infty} \frac{m^n c^{2n} (x_D - k)}{a^n - mc(a-1) \frac{a^n - m^n c^{2n}}{a - mc^2} (x_D - k)}$$

For a packed column where a continuous change of composition exists, the summation can be found by integrating between 1 and  $n$ . For a plate column, it gives a value of  $\Sigma x$  somewhat too low.

Edgeworth-Johnstone (5) found that the correct value can be obtained by integrating between 0.5 and  $n+0.5$  theoretical plates:

$$\Sigma x = nk + \int_{0.5}^{n+0.5} \frac{m^n c^{2n} (x_D - k) dn}{a^n - mc(a-1) \frac{a^n - m^n c^{2n}}{a - mc^2} (x_D - k)} = nk \\ + (x_D - k) \int_{0.5}^{n+0.5} \frac{dn}{\left[ 1 - \frac{mc(a-1)(x_D - k)}{a - mc^2} \right] \left[ \left( \frac{a}{mc^2} \right)^n + \frac{mc(a-1)}{a - mc^2} (x_D - k) \right]}$$

at the cutting point of batch fractionation where the reflux ratio is finite.

If the column is not empty at the beginning of the distillation, its contents must be added to the original charge in setting up the equations for material balance in the derivation for the expression of yield fraction.

**2. Application of Eshaya's Method.** With the aid of Smoker's Equation (12), Equations (36) and (39) are derived for the calculation of yield fraction of a batch fractionation, with a finite reflux ratio at the cutting point. The assumption involved is the validity of Smoker's equation in which constant relative volatility is assumed.

In the case of a nonideal solution, relative volatility varies greatly with the

Let

$$\frac{mc(a-1)(x_D - k)}{a - mc^2} = U' \quad (38)$$

(36) can be transformed into:

$$\Sigma x = nk + (x_D - k) \int_{0.5}^{n+0.5} \frac{dn}{(1 - U') \left( \frac{a}{mc^2} \right)^n + U'} \\ \Sigma x = nk + \frac{(x_D - k)}{U'} \left[ n - \log \frac{U' + (1 - U') \left( \frac{a}{mc^2} \right)^{n+0.5}}{U' + (1 - U') \left( \frac{a}{mc^2} \right)^{0.5}} \right] \quad (39)$$

The value of  $\Sigma x$ , calculated by Equation (39), is then multiplied by  $Q$  moles of holdup per theoretical plate, to give the total amount of holdup in the column

concentration. Eshaya (7) found that his method for the calculation of

theoretical plates can be applied to nonideal systems, as well as ideal ones, provided the vapor-liquid equilibrium curve could be given in the form of a power series:

$$y = q_1(x) = A_s + B_s x + C_s x^2 + \dots + S_s x^s \quad (40)$$

Substitution of Equation (40) into Equation (23), integration and rearrangement leads to:

$$m_1 = A + \frac{1}{x_D - x_n} \left[ \frac{B}{2} (x_D^2 - x_n^2) + \frac{C}{3} (x_D^3 - x_n^3) + \dots + \frac{S}{s} (x_D^s - x_n^s) - 2.303 x_D (1-m) \ln \frac{x_D}{x_n} \right] \quad (41)$$

In general, three terms in Equation (40) are sufficient to represent the vapor-liquid equilibria of the usual nonideal system, in such a case Equation (41) simplifies considerably and becomes:

$$m_1 = A + \frac{B}{2} (x_D + x_n) + \frac{C}{3} (x_D^2 + x_D x_n + x_n^2) - \frac{x_D (1-m)}{x_D - x_n} \ln \frac{x_D}{x_n} \quad (42)$$

Where

$$x_n = 1/m [Ax_B + Bx_B^2 + Cx_B^3 - b]$$

Substitution of Equation (29) into (34) gives the expression for number of moles of distillate collected up to the cutting point.

$$D = \frac{Fx_f - Q\Sigma x - Fx_D \left( \frac{m}{m_1} \right)^{n+1} + nQx_D \left( \frac{m}{m_1} \right)^{n+1}}{x_D - x_D \left( \frac{m}{m_1} \right)^{n+1}}$$

$$\text{Yield fraction } Y = \frac{Dx_D}{Fx_f} = \frac{1}{Fx_f} \left[ \frac{Fx_f - Q\Sigma x - x_D \left( \frac{m}{m_1} \right)^{n+1} (F - nQ)}{1 - \left( \frac{m}{m_1} \right)^{n+1}} \right] \quad (43)$$

$\Sigma x$  can be found by the same method employed previously,

$$\begin{aligned} \Sigma x &= \sum_{n=1}^{\infty} x_n = \sum_{n=1}^{\infty} x_D \left( \frac{m}{m_1} \right)^n \\ &= \int_{0.5}^{n+0.5} x_D \left( \frac{m}{m_1} \right)^n dm \end{aligned} \quad (44)$$

Integration and substitution of limits of Equation (44) gives:

$$\Sigma x = x_D \left[ \frac{\left( \frac{m}{m_1} \right)^{n+0.5} - \left( \frac{m}{m_1} \right)^{0.5}}{\ln \left( \frac{m}{m_1} \right)} \right] \quad (45)$$

Where  $m_1$  can be calculated from Equation (42).

With the application of Eshaya's method, Equations (43) and (45) are derived for the calculation of yield fraction of batch fractionation with finite reflux ratio at the cutting point. These expressions are much simpler than those derived with the application of Smoker's

method in a column with ten theoretical plates. The feed contains 40 mole % of chlorobenzene and the composition of overhead product is specified as 98% of the latter.

The average relative volatility is 1.8896 and the holdup per plate per mole of the feed is 0.01. Yield fractions at different reflux ratios calculated by Smoker's equations for both ideal column and column with holdup are presented in Table 1, together with the results calculated by Edgeworth-Johnstone. It is noted that the average percentage of deviation between two methods is within -4%. In the case of a column with greater number of theoretical plates, the agreement must be excellent.

### Complex Mixtures

Hengstebeck (9) presented a simple graphical method for solving continuous multicomponent distillation problems which is a modified McCabe-Thiele method. Multicomponent systems are treated as binary systems of the key components with liquid and vapor quantities in the distilling column adjusted to "effective" quantities which are calculated upon the following assumptions:

- Negligible concentrations in the stripping section of components more volatile than the key components
- Negligible concentration in the rectifying section of components less volatile than the key components
- Values for the "constant concentrations" of the components lighter and heavier than the keys. The "effective" liquid and vapor quantities, i.e., quantities of the keys present in the liquid and in the vapor, are approximated by subtracting the "constant" quantities calculated from the total liquid and vapor quantities. Composition of feed, overhead and bottom products, in terms of mole fraction of the light key, are also converted into "effective mole fraction" of the light key. These values of "effective quantities" are used then to determine the required number of theoretical plates by a McCabe-Thiele construction in which the keys are treated as a binary system.

Smoker's equation and Eshaya's method which are applied to solve bin-

TABLE I.—COMPARISON OF YIELD FRACTION CALCULATED BY EDGEWORTH-JOHNSTONE (6) AND BY EQUATION OF SMOKE'S FORM

	Reflux Ratio	Still Composition $x_n$	Yield Fraction from an Ideal Column $F_e$		Yield Fraction from a Column with Holdup $F$	
			Edgeworth-Johnstone	Smoker's	Edgeworth-Johnstone	Smoker's
	7	0.260	0.476	0.502	0.319	0.356
	12	0.157	0.728	0.728	0.563	0.584
	20	0.137	0.808	0.807	0.650	0.667

ary distillation problems, can be applied to this effective binary system. In the case of batch rectification where only the enriching column is involved, the assumption made by Hengstebeck might conform more closely to the actual column condition. In a mixture containing components 1, 2, 3 to be separated into "pure fractions" by batch rectification the first overhead fraction collected contains nearly pure component 1 with small amount of component 2. Components 1 and 2 are chosen as the key components. "Effective mole fractions" of component 1 in the overhead product and original charge to the still are calculated by Hengstebeck's method. Equations (17), (31), (36), and (43) can be used to calculate the yield fraction of component from a column with and without holdup, provided the relative volatility of component 1 with reference to component 2 is used. The reflux ratio used in these equations is the same as the actual one at the cutting point.

**Illustration.** A mixture of chlorobenzene and bromobenzene containing 40% of the former is separated by batch rectification under the atmospheric pressure to give an overhead product of 98 mole % of chlorobenzene. Moles of material held up in the column per theoretical plate per mole of the feed is 0.01. If the distilling column is equipped with plates equivalent to ten theoretical plates, calculate the yield fraction if a reflux ratio of 12 is used at the cutting point. The pressure drop through the column can be neglected for the purpose of the calculation. Barometer reading during distillation is normal.

#### Solution:

a for the system = 1.8896

$$m = R/(R+1) = \frac{12}{12+1} = 0.923$$

$$b = x_D/(R+1) = 0.98/(12+1) = 0.0754$$

Solving (4) and (5) and substituting the values of m, b, and a into the final expression, K is found to be equal to 0.09145

$$C = 1 + (a-1)K = 1 + (1.8896 - 1) \cdot 0.09145 = 1.08135$$

Using (38)

$$\begin{aligned} U' &= mc(a-1)(x_D-K)/(a-mc^2) \\ &= 0.923 \times 1.08135(1.8896 - 1)(0.98 - 0.09145)/1.8896 - 0.923 \times 1.08135 \\ &= 0.97361 \end{aligned}$$

$$a/mc^2 = 1.75079$$

Using (39),

$$\begin{aligned} x &= nk + \frac{(x_D-K)}{U'} \left[ n - \frac{\log \frac{U' + (1-U')(a/mc^2)^{n+1}}{U' + (1-U')(a/mc^2)^n}}{\log (a/mc^2)} \right] \\ &= 10 \times 0.9145 + \frac{(0.98 - 0.09145)}{0.97361} \left[ 10 - \frac{\log \frac{0.97361 + (1 - 0.97361)1.75079^{10.1}}{0.97361 + (1 - 0.97361)1.75079^9}}{\log 1.75079} \right] \end{aligned}$$

$$= 6.235$$

$$U = (1-U')(a/mc^2)^{n+1} + U' = (1-0.97361)(1.07928)^{10} + 0.97361 = 13.47835$$

Using (36),

$$\begin{aligned} \text{Yield fraction} &= Y = \frac{x_D}{FX_1} \left\{ \frac{Fx_1 - QZ - (F-nQ)(K + (x_D - K)/U)}{(x_D - K)(1 - 1/U)} \right\} \\ &= \frac{0.98}{40} \left\{ \frac{10 - 6.2350 - (100 - 10) \left( \frac{0.09145 + \frac{0.98 - 0.09145}{13.47835}}{0.98 - 0.09145} \right)}{(0.98 - 0.09145) \left( 1 - \frac{1}{13.47835} \right)} \right\} \\ &= 0.58379 \end{aligned}$$

#### Notation

A, B, C,

... a = constants in equation of equilibrium curve

b = intercept of operating line with Y axis

c = 1 + (a - 1)k

F, D, L = total moles of charge, distillate and residue respectively

k = X—coordinate of point of intersection of operating line and equilibrium curve

m = slope of operating line

m<sub>1</sub> = slope of "fictitious equilibrium line"

R = reflux ratio at the cutting point

$$M = \frac{mc(a-1)}{a-mc^2}$$

n = number of theoretical plates in column

Q = moles held up in column per theoretical plate

$$U = [1 - M(x_D - k)] \left( \frac{a}{mc^2} \right)^{n+1} + M(x_D - k)$$

$$U' = \frac{mc(a-1)(x_D - k)}{a - mc^2}$$

S = exponent in last term of Maclaurin series, an even number

x<sub>D</sub>, x<sub>B</sub>, x<sub>B'</sub>

x<sub>1</sub>, x<sub>n</sub>, etc. = mole fraction of more volatile component in charge, distillate residue on first plate, on nth plate and etc.,

counting from top of column respectively

x<sub>f</sub>', x<sub>D</sub>', x<sub>B</sub>',

x<sub>1</sub>', x<sub>n</sub>', etc. = mole fraction of same referring to new origin in Smoker's method

y<sub>B</sub>, y<sub>1</sub>, y<sub>n</sub>:

etc. = mole fraction of more volatile component in vapor from still, first plate, nth plate and etc.

y<sub>B</sub>', y<sub>1</sub>', y<sub>n</sub>',

etc. = mole fraction of same referring to new origin in Smoker's method

Y = yield fraction

a = relative volatility

B = a - 1

$\Sigma x$  = sum of plate-to-plate liquid composition

$$x_1 + x_2 + \dots + x_n$$

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# HEAT TRANSFER IN STABLE FILM BOILING

LeROY A. BROMLEY

University of California, Berkeley, California

By the use of equations, which are derived from a few simple premises and well verified by extensive experimental data, it is possible to calculate coefficients of heat transfer to be expected in natural convection stable film boiling from a horizontal tube.

The method employed for the derivation may be applied to derive equations for heat-transfer coefficients to be expected in film boiling from any other shape. Equations are derived for the case of film boiling from a vertical tube or a vertical plane surface.

THE name, film boiling, has been given to that type of boiling which occurs when a complete vapor film exists between the heated surface and the boiling liquid. Nucleate boiling, in which the vapor originates from individual points on the hot surface, is the type of boiling most generally encountered (13) and usually is to be preferred because of the large heat-transfer coefficients that can be obtained.

The basic equation for heat transfer is written:

$$q = hA\Delta t \quad (1)$$

$q$  represents the heat transferred per unit time;  $h$  is the coefficient of heat transfer;  $A$  represents the area;  $\Delta t$  is the temperature difference between the hot surface and the boiling liquid.

It is the purpose of this work to develop a sound theory which will predict the coefficients of heat transfer to be expected when there is stable film boiling. Experimental work was all carried out on the boiling of liquids from the outside of horizontal tubes, although the equations are also developed for the case of free convection stable film boiling from a vertical tube.

## Occurrence of Film Boiling

Operation of jets or rockets frequently involves the contact of a boiling liquid with hot surfaces; this is the condition for film boiling.

Film boiling usually occurs in the

NOTE: Supplemental and calculated data comprising Tables 1-19 are on file (Document 2750) with the American Documentation Institute, 1719 N Street, N.W., Washington, D.C. Data can be obtained by remitting 50 cents for a microfilm and \$1.90 for photoprints.

Thus it is apparent that the phenomenon of film boiling is real and that a sound theory by which to predict heat-transfer coefficients is needed.

## Previous Work on Film Boiling

An extensive survey of the known facts about film boiling up to 1937 has been published (2). Recent data (1937-48) have been reviewed and discussed (3). From this the following qualitative facts may be listed.

## Metastable Film Boiling

1. All high-speed photographs of metastable film boiling indicate definite waves or ripples in the vapor-liquid boundary (13, 6, 22, 23). The film sometimes appears to build up alternately and collapse (7a). Sometimes the liquid appears to contact the tube continuously at numerous points on the tube.

2. The heat-transfer coefficients are higher than would be predicted if the film were perfectly smooth. This is at least partially due to the ripples (3).

3. The nature of the hot solid surface is important but decreasingly so as the stable film-boiling region is approached (3, 21, 20, 23).

4. An increase in pressure, while boiling is maintained, especially when the pressure approaches the critical value, lowers the critical  $\Delta t$  and the  $(q/A)_{max}$ , thus making it increasingly easy to get film boiling (5).

5. A decrease in the liquid vapor interfacial tension causes a lowering and shifting to the left of the metastable portion of the curve in Figure 1 (6, 15, 19). Such a decrease also shifts the critical temperature difference  $\Delta t_c$  appreciably to the left and downward. This effect is completely ignored by certain authors (11, 12).

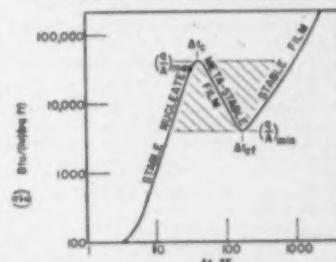


Fig. 1. Typical Boiling Curve.

## Theory

*Horizontal Tube.* A simple theory will be developed which will enable one to calculate the coefficients of heat transfer to be expected in stable film boiling (for natural convection) from the outside of a horizontal tube. The vapor film is in dynamic equilibrium for as it rises under the action of buoyant forces, vapor is added to it from the boiling liquid. The necessary heat is supplied by conduction and radiation across the film. This mechanism appears from visual observations to be the situation on about the lower two-thirds of a tube; here there appears to be a fairly smooth continuous film. There appears to be some local disturbance at the bottom of the tube but it is not great except at high fluxes. On the upper third of the tube, however, the situation is very complicated for in this part the bubbles form before rising. Since most of the heat will be transferred on the bottom two-thirds of the tube it would seem most important to have the theory fit the situation in this part of the tube.

Assumptions in the simple theory follow:

1. The liquid is separated from the hot tube by a continuous vapor blanket.

2. Heat travels through vapor film by conduction and radiation.

3. Vapor rises under the action of buoyant forces.

4. Vapor-liquid interface is smooth in that section of tube where most of the heat is transferred.

5. Rise of the vapor is retarded by the viscous drag on the tube and more or less on the liquid.

6. Latent heat of vaporization is the major item in the heat supplied to the vapor film.

7. The kinetic energy of vapor in film is negligible.

8. Vapor-liquid interface is smooth and continuous and is not affected by a variation in the vapor-liquid interfacial tension.

9. It is permissible to use an average value for the temperature difference between the hot tube and the boiling liquid and treat it as a constant value around the tube in the integrations. This approach to the problem is essentially that used by Nusselt (17) for condenser problems and has been shown (9) to be justified in the case of condensers to within the accuracy required for engineering calculations.

10. The boiling liquid is at its boiling point at the vapor-liquid interface.

11. For engineering calculations it will be satisfactory to evaluate all physical properties of the vapor at the arithmetic average temperature of the hot surface and the boiling liquid.

12. The combined effect of most of the errors in the foregoing assumptions may be corrected by evaluating a suitable "constant" factor to be determined from the experimental data.

The foregoing assumptions for the case of negligible radiation were expressed in mathematical equations

which are similar to Nusselt's equations for condensers with  $\rho p$  replaced by  $\rho(\rho_t - \rho)$ . Equation 2 results from the integration of the resulting differential equation. The constant should theoretically have the value 0.512 if the liquid surrounding the tube is assumed stagnant and 0.724 if the liquid moves completely freely with the vapor.

$$h_{eo} = (\text{const}) \left[ \frac{k^2 \rho (\rho_t - \rho) g k' c_p}{D \Delta t P r} \right]^{\frac{1}{4}} \quad (2)$$

All physical properties of the vapor are evaluated at the average temperature of the film. This average has been arbitrarily taken as the arithmetic average of the tube surface temperature and the boiling liquid temperature.

The assumption that the latent heat is so large that the heat required to heat the film is negligible may be seriously in error. Thus the dimensionless group in Equation (2), that is the constant, would be expected to be a function of the ratio of the heat required for vaporization to the heat used in raising the temperature of the film. That is to say,

$$(\text{const}) = f \left( \frac{2\alpha}{\Delta t c_p} \right) = f' \left( \frac{\Delta t c_p}{\lambda'} \right) \quad (3)$$

If the kinetic energy of the vapor in the film is not negligible then the derivation should be changed to include this kinetic energy term in Bernoulli's equation. A detailed analysis of this effect shows that

$$h_{eo} \left( \frac{D \Delta t P r}{k^2 \rho (\rho_t - \rho) g k' c_p} \right)^{\frac{1}{4}} = (\text{const}) \\ = f'' \left( \frac{\Delta t c_p}{\lambda' P r} \right) \quad (4)$$

where the constant is only a true constant in the simple theory (Equation (2)). Thus it can be seen that by plotting experimental values of the constant against the group  $\Delta t c_p / \lambda' P r$  the combined effect of kinetic energy in the vapor film Equation (4), and the heat capacity of the vapor in the film (Equation (3)) should be shown. Errors in other assumptions in the simple theory should show up also on this plot. The amount of flow of the liquid at the vapor boundary also affects the constant. It will be shown in the section on results that within the limit of experimental error there is no trend of the constant with the group  $\Delta t c_p / \lambda' P r$  and hence the errors in the simple theory either tend to cancel or are of small magnitude.

*Vertical Tube or Plate.* No experimental work is reported on natural convection film boiling from a vertical tube or plate but by applying the same

simple theory as for the horizontal tube, the following equation follows:

$$h_{eo} = (\text{const}') \left[ \frac{k^2 \rho (\rho_t - \rho) g k' c_p}{L \Delta t P r} \right]^{\frac{1}{4}} \quad (5)$$

$L$  is the distance along the tube or plate in the direction of vapor flow.

*Effect of Radiation.* Since interest is centered in the combined effect of radiation and convection, the effect of radiation on the convection coefficient should be studied. An attempt was made to put the effect of radiation directly into the differential equation for convection. The result was not readily soluble. It was therefore thought that a less rigorous but at least qualitatively correct approach was in order. Let us postulate that the radiation from the tube will be largely absorbed in a small thickness of the liquid and hence will produce vapor which will contribute to the vapor film thickness. This is equivalent to saying that the transmissivity of the liquid is low for thermal radiation. Since the total coefficient is merely the sum of the convection and radiation coefficients, one can write:

$$h = h_e + h_r \quad (6)$$

For any given value of  $h_m$  (the convection coefficient if there were no radiation) the pressure drop from the bottom to the top of the film, viscosity of the vapor, diameter of the tube and density of the vapor may be taken as constant. Hence, the weight flow,  $w$ , at any angle  $\theta$  measured from the bottom of the tube is proportional to the cube of the thickness of the film,

$$w \propto \theta^3 \quad (7)$$

If the contribution of the radiation to  $w$  is small, then, since the rate of increase of  $w$  with angle always decreases, as the angle is increased,  $w$  increases with  $H'$  (the total weight flow) to somewhat less than the first power as the radiation contribution is increased. If the radiation is already large, however, then  $w$  is more nearly proportional to  $H'$  and in any case the relation between  $w$  and  $H'$  is not far from a direct proportion. For a given  $h_{eo}$ , the thermal conductivity of the film will be approximately constant and hence, the convection coefficient,  $h_e$ , will vary nearly inversely as the thickness of the film. Since the temperature difference and the enthalpy difference of the vapor and liquid will also remain nearly constant, the total weight of material evaporated will be proportional to the heat-transfer coefficient. Thus

$$h_e \propto \frac{1}{a} \propto \frac{1}{w^{\frac{1}{3}}} \propto \frac{1}{H'^{\frac{1}{3}}} \propto \frac{1}{h^{\frac{1}{3}}} \quad (8)$$

Combining this with Equation (6),

and noting that when  $h_r$  is equal to zero there is no heat transferred by radiation and hence,  $h$  is equal to  $h_{eo}$ .

$$h = h_{eo} \left( \frac{h_{eo}}{h} \right)^{\frac{1}{4}} + h_r \quad (9)$$

Equation (9) gives us the approximate relationship between  $h$ ,  $h_{eo}$  and  $h_r$ . This equation is difficult to use because  $h$  occurs implicitly in it.

As long as  $h_r$  is smaller than  $h_{eo}$ ,

$$h = h_{eo} + \frac{3}{4} h_r \quad (10)$$

to within five per cent of the  $h$  from Equation (9). If  $h_r$  is very large, one may use the following equation which gives the same relationship as Equation (9) between  $h$ ,  $h_{eo}$  and  $h_r$  to within three-tenths of one per cent, as long as  $h_r/h_{eo}$  is between zero and ten. This is certainly within any practical operating range.

$$h = h_{eo} + h_r \left[ \frac{3}{4} + \frac{1}{4} \frac{h_r}{h_{eo}} \left( \frac{1}{2.62 + \frac{h_r}{h_{eo}}} \right) \right] \quad (11)$$

The term  $h_r$  may be calculated by the following equation for parallel plates.

$$h_r = \frac{\sigma}{\frac{1}{e} + \frac{1}{a} - 1} \frac{T_H^4 - T_L^4}{\Delta t} \quad (12)$$

The graph in McAdams (13) (Fig. 27, p. 63) may be used to get  $h_r$  for black surfaces. This value may be multiplied then by the emissivity factor

$$\left[ \frac{1}{\frac{1}{e} + \frac{1}{a} - 1} \right]$$

to get the true  $h_r$ . In all the above it is assumed that the transmissivity of the liquid for thermal radiation is small (as it is for most liquids).

#### Apparatus

The apparatus (see Fig. 2) consists essentially of a carbon tube heating element, from which the boiling occurs, contained between holders in a 4-in. pyrex pipe tee. This apparatus has been described in detail (3).

The carbon tubes used were nominally  $\frac{1}{4}$ ,  $\frac{3}{8}$  and  $\frac{1}{2}$  in. One run was made with a  $\frac{3}{16}$ -in. stainless steel tube. The hole in the tube was used to accommodate a thermocouple. From the reading of this thermocouple it was possible to calculate the tube-surface temperature. The difference between the tube-surface temperature and the observed inside temperature of the tube was at most ten per cent of the temperature difference between the tube-surface and the boiling-liquid temperature. The thermocouple was also used to check the temperature uniformity along the tube. The heating was obtained as the product of the current through the tube by the voltage drop along a given section usually 5 in. in the center of the tube.

#### Experimental Procedure

Various parts of the apparatus (Fig. 2), were cleaned thoroughly. The tube to be used was polished. Copper inserts and the

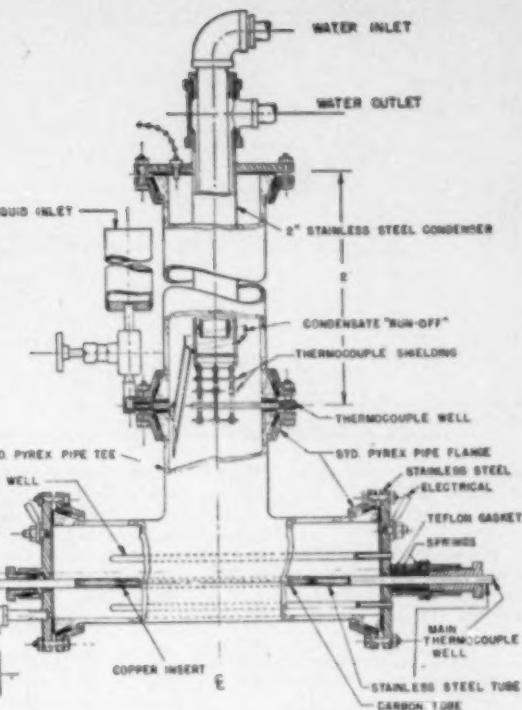


Fig. 2. Experimental Film-Boiling Apparatus.

stainless steel holders were cleaned with emery cloth to give good electrical contacts. The tube was put in place between the stainless steel holders and the packing glands at the sides of the apparatus were tightened to give a liquid seal. After assembly, the apparatus was filled with liquid to the desired level. Unless otherwise stated the level was between 1 and  $1\frac{1}{4}$  in. above the center of the tube. The external heater was turned on and current was passed through the tube until the liquid was boiling at the prevailing atmospheric pressure.

The heat input to the tube was increased to a high value for a few minutes to insure stable film boiling over the entire surface. Film boiling is evidenced by a smooth film on the sides of the tube. The current was then set at the desire value. Of the liquids which were run only water was difficult to get into the film-boiling range without burning out the tube. All data were taken with stable film boiling of the various liquids except for a few data taken with nucleate boiling of water for the purpose of evaluating roughly the thermal conductivity of the carbon (3).

The current was held constant and the potentiometer, which was connected to the thermocouple in the tube through the rotary thermocouple switch, was observed until steady conditions were established. This usually required only a few minutes. The reading of the potentiometer and on the voltmeter which was connected to the voltage probe (which was usually  $2\frac{1}{2}$  in. to the left of the center) were recorded. The thermocouple was removed and the voltage probe was moved to the same distance on the other side of the center and the voltage was then again recorded. The other voltage

terminal was fastened to one terminal of the apparatus. The voltage probe was then moved back to its former position and the thermocouple replaced to its center point position. This reading was usually compared with the first reading of the thermocouple and if no check was obtained the readings were repeated. At some point during the run readings were taken of all the other thermocouples. These readings were hardly necessary as the observed liquid temperatures vary at most a degree or two from the reported boiling points for one atmosphere and this is a relatively unimportant item in the theory. The external heater temperature has essentially no effect on the observed coefficients (3).

The thermocouple used in the tube temperature measurements was calibrated (3) at the boiling point of water, the melting point of tin and at the melting point of copper.

**Data.** Table I\* represents typical experimental and calculated data (20). Tables of data were taken on the following liquids: water, nitrogen, carbon tetrachloride, absolute ethyl alcohol, benzene, diphenyl oxide and *n*-pentane. Calculated data are also presented on mercury. Data of Pilling and Lynch (19) on the quenching of a hot nickel rod in boiling water and in soap solution are given.

To check the effect of tube diameter on heat-transfer coefficients, data were

\* (See footnote, p. 221.)

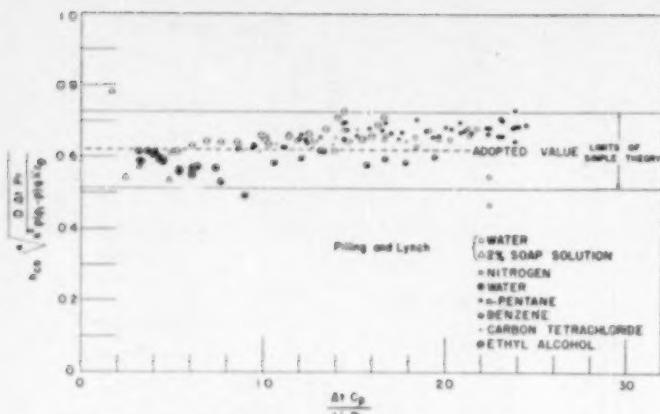


Fig. 3. Evaluation of "Constant" in Convection Eq. 2.

taken on pentane with carbon tubes of diameters: 0.352, 0.238 and 0.469 in., and with a stainless steel tube of diameter of 0.188 in.

Physical constants which were used in the calculations were obtained from the literature which was searched up to 1948 and are summarized in graphical form (3).

$\Delta t$  is the calculated value of the difference in temperature between the tube surface and the boiling liquid.

The  $h$  is the over-all calculated coefficient of heat transfer based on the observed data.  $h_{eo}$  is the calculated value, from Equation (9), of the coefficient of heat transfer to be expected if there were no radiative heat transfer.

$const$  is the value which appears in Equation (2). This value was calculated from the value of  $h_{eo}$ ,  $\Delta t$ , the tube diameter and the physical constants ( $\beta$ ) of the liquid and its vapor.

The quantity,  $\Delta t_c/\Delta t'Pr$ , is important in that the extended theory, Equation (4), indicates that the  $const$  should be some function of this dimensionless group.

The external heater temperature and the observed liquid and vapor temperatures are not included. It has been shown (3) that the results are not affected by changes in heater temperature. Liquid and vapor temperatures were in all cases close to the published values for the normal boiling point at one atmosphere.

All data in the tables were taken with the entire tube in stable film boiling. Liquids were all reagent or better.

At the highest tube temperatures there was appreciable decomposition of the

various liquids. Although no attempt was made to correct for this in the physical properties used to evaluate the constant, the residual alcohol in one run was analyzed by fractional distillation and found to be better than 99.5% absolute alcohol.

## Results

Figure 3 is a plot of the experimental values of the constant in Equation (2), as given in Tables 1-21, against the parameter  $\Delta t_c/\Delta t'Pr$ . It can be seen that there is perhaps a slight trend of the constant with  $\Delta t_c/\Delta t'Pr$  but it is certainly not conclusive and in fact it is to be noted that the data for each liquid which were taken at the smallest temperature differences, and hence are the most accurate, lie almost on a straight line at the adopted value of the constant of  $0.62 \pm 0.04$ . This tends to indicate that at least for the range of liquids chosen there is no trend of the constant with the physical characteristics of the liquid, other than with density which occurs in Equation (2). These liquids do not, however, cover a wide range of viscosity and it is still possible that a viscous liquid might give a value of the constant as low as 0.52.

Equation (2) then becomes:

$$h_{eo} = 0.62 \left( \frac{k^2 \rho (\rho_1 - \rho) g h' c_p}{D \Delta t' Pr} \right)^{1/4} \quad (13)$$

TABLE I  
Run Number 944  
Experimental and Calculated Data on Film Boiling of Water  
0.352-in. O.D. Carbon Tube

Point No.	Amp.	Volts $\times 10^3$	$t_s$ sec	$\Delta t$ $^{\circ}\text{F}$	B.t.u.			$h_{eo}$ $\text{hr}^{-1} (\text{sq ft}) ({}^{\circ}\text{F})^{-1}$	$h_{eo}$ $\text{hr}^{-1} \text{ft}^{-2} {}^{\circ}\text{F}$
					(hr)	(sq ft)	( ${}^{\circ}\text{F}$ ) $^{-1}$		
1	100	6.41	36.35	1296	48.7	33.2	0.55	0.61	
2	90	6.3	32.50	1174	43.0	32.6	0.55	0.53	
3	80	5.87	28.95	1002	41.7	33.4	0.59	0.45	
4	70	5.55	23.75	915	40.8	34.7	0.62	0.36	
5	110	7.63	40.15	1495	50.0	34.3	0.52	0.77	

The inside diameter of the carbon tube is 0.125 in.

\* Voltage was measured across the center 5 in. of the carbon tube.

The effect of the tube diameter on the coefficients of heat transfer is shown clearly in Figure 4. This indicates that a decrease in tube diameter, other things being equal, results in an increase in the coefficient of heat transfer.

Equations (2) or (13) would predict that the coefficient of heat transfer,  $h_{eo}$ , should vary inversely as the one-fourth power of the diameter. Figure 5 shows that within the limit of experimental error this is certainly the case.

Data for the stainless steel tube fit on the same curve as the carbon tube and also the data of Pilling and Lynch (19) on a nickel rod (Equation (13)). From this it is apparent that the physical or chemical character of the tube or tube surface has little or no effect as long as it is fairly round and smooth. This is what the theory predicts.

It might be expected that the shape of the containing vessel or the depth of emersion of the tube would be at least somewhat important. The latter effect was checked by an experiment in which the liquid level which was normally at least one inch above the tube was lowered until the tube was about one-sixth exposed. In this case there was no bubble formation but the rising vapor merely escaped directly into the vapor phase. This caused but little disturbance of the liquid. The coefficient for this run is the same as that when the tube is covered. This tends to indicate that convection currents set up in the liquid by the rising bubbles do not substantially increase the heat-transfer coefficient. It is realized that the evidence is as yet too meager to be conclusive on this point and indeed, if several tubes were located above or near each other there might be an appreciable effect on the heat transfer.

Figure 6 is a plot of the coefficients of heat transfer in film boiling from a heated 0.350-in. O.D. horizontal carbon tube to liquid nitrogen. The lowest curve is the calculated coefficient of heat transfer by radiation alone using a value of 0.8 for the emissivity of carbon. The intermediate curve is the calculated coefficient of heat transfer,  $h_{eo}$  (Equation (13)). This is the coefficient of heat transfer which would be expected if there were no radiation. The upper curve is the calculated coefficient of heat transfer using Equation (9); this includes both the contribution of radiation and convection. It may be seen that the experimentally measured values of  $h$ , represented by the open circles, agree fairly well with the calculated coefficients. The solid points are the experimental values of  $h_{eo}$  calculated from the measured values of  $h$ , using Equation (9). Equation (11) might just as well have been used since it is numerically equivalent to Equation (9).

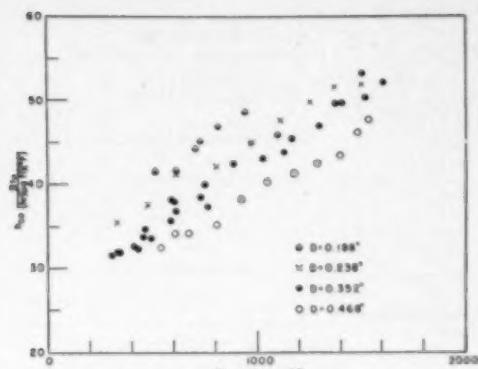


Fig. 4. Effect of Tube Diameter on Heat-Transfer Coefficient for Film Boiling of n-Pentane.

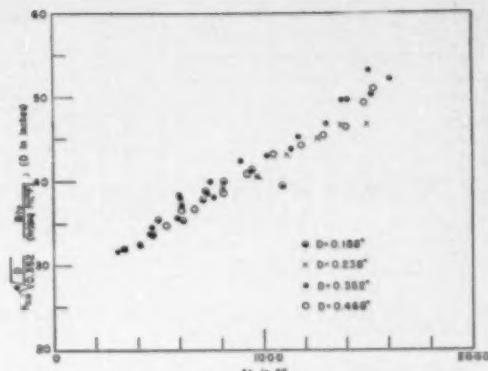


Fig. 5. Verification of Predicted Inverse One-Fourth Power Dependence of Heat-Transfer Coefficient on Tube Diameter for Film Boiling of n-Pentane.

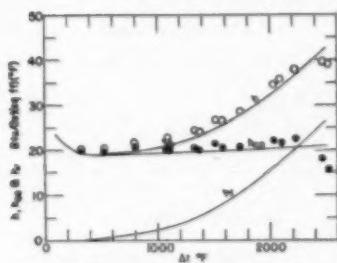


Fig. 6. Film Boiling of Nitrogen from 0.350 in. Carbon Tube.

Since a plot of  $h_{\text{in}}$  against  $\Delta t$  is of more value perhaps than one of  $h$  against  $\Delta t$ , Figures 7-13 include only the former. The curves are the calculated values and the points are the experimental values. It is felt that the measured points are in all cases of higher accuracy than the calculated curves because of the uncertainty in the physical properties of the liquid, its vapor, and the tube.

No concerted effort was made to determine the minimum critical heat flux or the critical temperature difference in the film boiling. Data (19) indicate clearly that it is possible to go to much lower values of the temperature of the tube in film boiling when soap is dissolved in the water. This indicates that a decrease in surface tension of the liquid lowers the minimum critical heat flux and the temperature corresponding to this heat flux.

Recent data (12a) on film boiling of water from platinum wires of from 0.004 to 0.024 in. diameter indicate that the theory is not accurate within this range of wire size; the error ranged from about 30% to 100% as size of wire is decreased from 0.024 to 0.004 in.

### Conclusions

Stable film boiling may be characterized as follows:

1. The liquid-vapor interface is substantially smooth (3) except at high heat fluxes. It is, of course, always uneven at its top surface due to bubble formation.

2. Heat-transfer coefficients are independent of the tube material except for the radiation contribution (3).

3. The effect of any variable such as pressure may be calculated from its effect on the physical properties of the liquid and its vapor.

4. A decrease in vapor-liquid interfacial surface tension produces no change in the calculated coefficients but such a decrease in interfacial tension does reduce the minimum critical heat flux and the temperature corresponding to it (19, 6).

5. If the liquid is below the boiling point it is possible still to have a complete vapor blanket around the hot object but the coefficients of heat transfer are higher than those to a liquid at the boiling point (19). This phenomenon occurs in the quenching of steel, etc.

6. This type of boiling is usually encountered in mercury boilers (14, 8, 9, 7). Heat-transfer coefficients to boiling mercury are usually smaller than to nonboiling mercury (24, 25, 3). Addition of potassium to the mercury which should tend to wet the solid surface does not help prevent vapor binding (24).

7. Vigorous agitation of the boiling liquid and its vapor (such as rapid two-phase flow through tubes) increases the heat-transfer coefficients over those for natural convection film boiling (24).

8. By the use of Equations (13) or (2), (12) and (11), which are derived from a

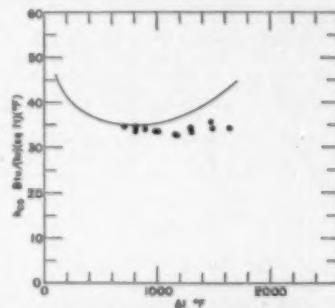


Fig. 7. Film Boiling of Water from 0.351 in. Carbon Tube.

few simple premises and well verified by extensive experimental data, it is possible to calculate coefficients of heat transfer expected in natural convection stable film boiling from a horizontal tube. If the amount of heat transferred by radiation is not more than half the total heat transferred, i.e., the temperature of the tube is not too high, the simplified Equation (10) may be used in place of Equation (11). The amount of heat transferred per unit time may then be calculated by Equation (11).

For simplified calculations for the liquids studied the experimental points or calculated curves in Figures 6-13 may be used together with Equation (13) to estimate heat-transfer coefficients in film boiling for

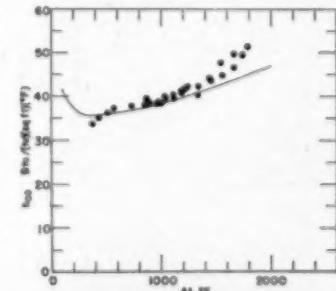


Fig. 8. Film Boiling of Ethyl Alcohol from 0.352 in. Carbon Tube.

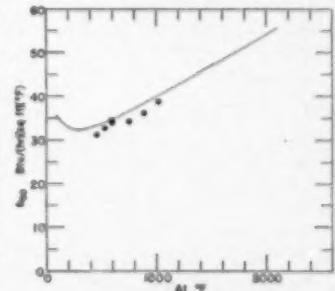


Fig. 9. Film Boiling of Benzene from 0.352 in. Carbon Tube.

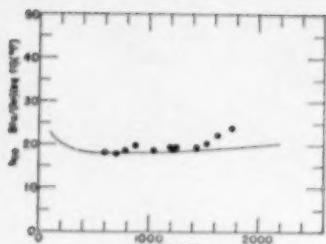


Fig. 10. Film Boiling of Carbon Tetrachloride from 0.352 in. Carbon Tube.

the given liquid from tubes of other diameters. The theory is restricted to tubes of such a diameter that the thickness of the film is small compared with the diameter of the tube, although it appears to hold fairly well down to tubes of 0.040-in. diameter.

The method employed for the derivation which may be found in the section "Theory" may be applied to derive equations for heat-transfer coefficients to be expected in film boiling from any other shape.

Equation (5) results from the application of the method to the case of the film boiling from a vertical tube or vertical plane surface.

### Notation

- $A$  = heat-transfer area, sq.ft.
- $a$  = thickness of film, ft.
- $c_p$  = specific heat of vapor at constant pressure, B.t.u./lb. ( $^{\circ}$ F.)
- $D$  = O.D. of tube, ft.
- $f$  = function
- $g$  = acceleration of gravity =  $4.17 \times 10^9$  at sea level, ft./hr. (hr.)
- $h$  = subscript denoting heated tube
- $h$  = film coefficient of heat transfer, B.t.u./hr. (sq.ft.) ( $^{\circ}$ F.)
- $h_c$  = convection coefficient of heat transfer (see Equation (6)), B.t.u./hr. (sq.ft.) ( $^{\circ}$ F.)
- $h_{eo}$  = film coefficient of heat transfer if there were no radiation, B.t.u./hr. (sq.ft.) ( $^{\circ}$ F.)

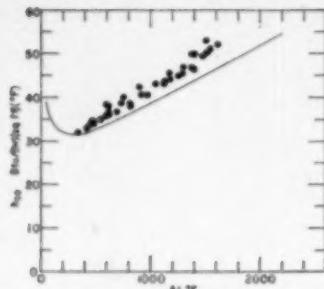


Fig. 11. Film Boiling of n-Pentane from 0.352 in. Carbon Tube.

$h_r$  = radiation coefficient of heat transfer (see Equation (12)) B.t.u./hr. (sq.ft.) ( $^{\circ}$ F.)

$k$  = thermal conductivity of vapor, B.t.u./hr. (ft.) ( $^{\circ}$ F.)

$L$  = length of tube, ft.

$l$  = subscript denoting liquid

$m_v$  = subscript denoting millivolts, chromel-alumel thermocouples

$q$  = heat flow, B.t.u./hr.

$Pr$  = Prandtl number, of vapor =  $\frac{\mu c_p}{k}$

$T$  = temperature,  $^{\circ}$ R.

$t$  = temperature,  $^{\circ}$ F.

$\Delta t$  = temperature difference between hot surface and liquid at its boiling point,  $^{\circ}$ F.

$t_i$  = temperature of inside of tube,  $^{\circ}$ F.

$W$  = weight evaporated on entire tube, lb. mass/hr.

$w$  = weight evaporated up to any angle  $\theta$  measured from the bottom of tube, lb. mass/hr.

$\alpha$  = absorptivity of the liquid (usually near unity)

$\epsilon$  = emissivity of hot tube

$\lambda$  = latent heat of vaporization at boiling point, B.t.u./lb. mass

$\lambda'$  = difference in heat content between vapor at its arithmetic average temperature and li-

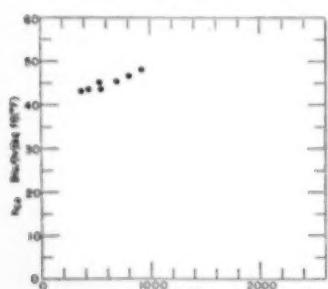


Fig. 12. Film Boiling of Diphenyl Ether from 0.352 in. Carbon Tube.

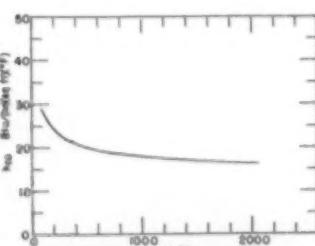


Fig. 13. Film Boiling of Mercury from 0.352 in. Carbon Tube.

quid at its boiling point, B.t.u./lb. mass

$\mu$  = viscosity of vapor, lb. mass/(hr.) (ft.)

$\rho$  = density of vapor, lb. mass/(cu. ft.)

$\rho_l$  = density of liquid, lb. mass/cu. ft.

$\sigma$  = Stefan-Boltzmann constant,  $0.1713 \times 10^8$  B.t.u./hr. (sq. ft.) ( $^{\circ}$ R.) $^4$

### Acknowledgment

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### Discussion

**W. F. Seyer** (University of California, Los Angeles, Calif.): What is the effect of pressure on this film boiling?

**LeR. A. Bromley:** The effect of pressure can be calculated by merely a consideration of the effect of the various groups within the fourth-root term in Equation (2). For instance, if you know the effect of pressure on the conductivity, you can substitute merely an appropriate value of the conductivity in the equation, similarly for any other term (e.g., heat capacity, density, etc.).

**V. D. Sanders** (University of Calif., Los Angeles, Calif.): Stable film boiling for water has been specified as the region of boiling between a temperature potential of 400° F., and that potential at which radiation becomes appreciable (1). The author has developed a means of predicting the contribution of convection in the vapor film surrounding the heated surface in this mode of heat transmission. The effect of radiation is also presented by the author, but a sound evaluation of this portion of the work will require a more careful examination than is given.

An analysis of an idealized system is at best only an approximation, and the validity of the latter is governed by the applicability of the qualifying postulates. With this in mind, the following comments are offered:

I. In the description of stable film boiling, it is stated that a smooth film of vapor covers the bottom two-thirds of the tube. Bubbles are formed and leave the film over the remaining one-third portion of the tube. If considerable agitation accompanies the mechanism of the bubble formation, as is the case for other types of boiling, the unit thermal conductance may be greater over this region than that over which the viscous vapor film flows. This would cause a calculated value to be lower than a measured value, if the former were based on a film covering the entire heated surface. In this case, a more correct value of unit thermal

conductance is an integrated average with respect to area.

2. The author defines the local unit conductance as the ratio of the vapor thermal conductivity (at the arithmetic average of the temperature in the film) to a local film thickness. This implies zero heat capacity and a flat velocity distribution in the film, as would be the case for a slug of vapor sliding between walls of different temperature. It has been shown that use of a similar technique yields a fair approximation for heat transfer in certain cases for flow in ducts (2). But, if vapor is being generated along the portion of the surface, and the heat required to superheat the vapor in the film is appreciable (for water vapor at atmospheric pressure and 1600° F., this quantity is 40% of the total enthalpy), this approximation may not be valid.

3. The analysis does not consider convection in the liquid about the vapor-liquid interface. For water at a pressure of one atmosphere boiling moderately over a flat plate, it was shown by Jakob and Fritz (3), that the order of superheat of the bulk liquid is of the order of  $\frac{1}{2}$ ° F. Undoubtedly, greater superheats exist in the vicinity of the interface. Also, the presence of the vapor film offers a smooth surface to the bulk liquid without the agitation accompanying nucleate boiling. Thus, in the absence of impurities and dissolved gases, the temperature of the vapor-liquid interface would be greater than that of the bulk liquid, so that perhaps natural convection heat transfer from the vapor film would approach appreciable magnitudes. It should be noted, however, that at a given pressure, the heat convected would be independent of the tube surface temperature.

**LeR. A. Bromley:** Mr. Sanders states the theory was restricted to the region between 400° F. and where radiation becomes appreciable. It is restricted to the region of stable film boiling. I did not state that the lower limit was 400°; that remains to be determined for the specific material and substance. Radiation does not limit the upper range of the theory for at the highest measured temperatures the radiation contribution was sometimes as much as 50% of the total heat transfer.

**V. D. Sanders:** I was quoting the reference by Farber and Scorah.

**LeR. A. Bromley:** It is true that in the derivation for the simplified theory, the heat capacity of the film is neglected. However, in the extended derivation, it is shown that the effect of heat capacity together with other assumptions should show up in Figure 3 where the dimensionless group involving the coefficient of heat transfer and other physical properties to the one-fourth power is plotted against  $\Delta C_p / \lambda^4 Pr$ . Other effects would show up on that same plot. Since the points did not deviate widely from a horizontal line on the graph, this shows that the effect of  $C_p$  is small or at least cancelled to a certain extent by other poor assumptions.

I take issue with your statement that a flat velocity distribution was assumed. A parabolic velocity distribution, which is the kind you would expect, was assumed. The effects that you noted on

superheating of the film, at the boundary between the vapor and the liquid which, as Jakob points out, is only a degree or so, should have no important effect on the heat transfer from the tube as this theory is applicable only for high temperature differentials between the tube and the liquid.

**Anonymous:** Would the movement of the liquid over the heated surface influence your coefficients seriously?

**LeR. A. Bromley:** Yes, undoubtedly it has an effect on the heat transfer. Two extreme cases were considered in the derivation, one where the liquid was a jelly, i.e., did not move at all, and the other where the liquid was so fluid that it exerted no drag on the rising vapor. Certainly these are two extreme cases. It was difficult to see how the liquid could move more rapidly when in natural convection than the vapor itself would move if no drag were exerted on it at the boundary. These assumptions produce a maximum variation of the constant in Equation (2), between 0.512 and 0.724. Undoubtedly the liquid flow influences the coefficient, but for the single tube in this particular geometry, the effects were such that the coefficient was 0.62. I don't feel the coefficient would be influenced markedly if the geometry were changed. As a matter of fact, one set of data by Pilling and Lynch on quenching of a nickel rod was from a system whose geometry was considerably different from mine, yet the coefficients were similar. If the liquid were forced over the tube at a high velocity it should be possible to increase the constant well above 0.724.

**Anonymous:** Maybe I didn't get the unit of heat-transfer rate correct. It seems low to me though for boiling. Could you give us the units again, and if they are low, tell us why?

**LeR. A. Bromley:** Those coefficients were low, and they are for the range of what I term stable film boiling. It is not the type of boiling that one normally encounters in a commercial boiler. Their temperature differences are low, and the coefficients high, surface coefficients as high as 10,000 B.t.u./hr. (sq.ft.) (°F.). The measured coefficients are all given and are in the order of magnitude of from 15 to 80 B.t.u./hr. (sq.ft.) (°F.).

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(Presented at Tenth Regional Meeting, Los Angeles, Calif.)

*At first glance it would appear that rocket performance is somewhat extraneous to the chemical engineering field . . . admittedly it is an unusual subject for coverage by Chemical Engineering Progress but it is in a new field where chemical engineering techniques and theory are important tools . . . this is part of the pioneering symposia from the Los Angeles Regional Meeting last year. . . .*

# PROBLEMS OF COMBUSTION

## Liquid-Propellant Rocket Motors

R. B. CANRIGHT

California Institute of Technology, Pasadena, California

This survey paper first describes a liquid-propellant rocket motor, its function, and ways by which its function is accomplished. Rocket performance and design parameters are defined. Chemical reactions in the rocket are discussed, on the basis of present semiempirical knowledge. In this category are mentioned the influence of the injector, the chamber, and the nozzle upon combustion. Finally, use of noncarbonaceous fuels is emphasized, and, as an example, experimental data from the systems  $\text{NH}_3\text{-O}_2$  and  $\text{C}_6\text{H}_5\text{NH}_2\text{-RFNA}$  are compared.

THE liquid-propellant rocket motor is a power plant which is being developed for use in applications where a controllable high thrust is desirable for a short period of time ( $\frac{1}{2}$  to 5 min.). The thrust-volume and thrust-weight

ratios of the rocket motor itself are much higher than for any other power plant, but the extremely high propellant consumption of the motor (approximately 15 to 18 lb./(hr.)(lb. thrust) limits its use to short-duration applications. This high propellant consumption is due mainly to the fact that a rocket carries its own oxidizer, and thus does

not make use of air to oxidize its fuel. On the other hand, this apparent limitation makes possible the use of rockets in empty space, where no other power plant now known can operate. Another advantage of the rocket motor is the fact that it can be, when designed for certain purposes, the only power plant presently in use which has no moving mechanical parts.

The liquid-propellant rocket motor consists of only three major components: the injector, chamber, and nozzle, as shown in Figure 1. The injector serves to introduce the liquids into the chamber in such a manner that complete chemical reaction is attained in the shortest time and with the least possible volume. The chamber provides the volume in which the constant-pressure combustion occurs. The nozzle, which is always of the DeLaval contracting-expanding type, serves to collimate the combustion gases (see Fig. 2) and convert part of their thermal energy to kinetic energy, which is utilized to provide thrust.

The thermal energy associated with the combustion gases is high, since there is no excessive dilution of the combustion products with inert nitrogen, as is the case for air-fuel combustion. Theoretical flame temperatures for liquid-propellant rockets generally range from  $4000^{\circ}\text{--}9000^{\circ}\text{ F.}$ , although most propellants have maximum flame temperatures in the range from  $5000$  to  $6500^{\circ}\text{ F.}$  Because of the relatively small volumes of rocket motors, extremely high energy

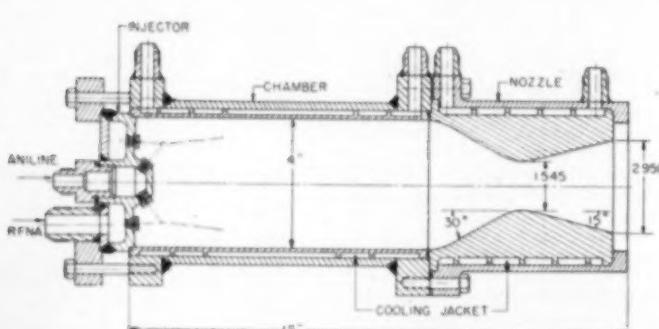


Fig. 1. Components of Test Rocket Motor.

loadings (of the order of 100 B.t.u./sec.) (cu.in.) or, in engineering units,  $6 \times 10^8$  B.t.u./hr. (cu.ft.) are attained; thermal loadings are likewise extremely high, since values up to  $5 \times 10^6$  B.t.u./hr. (sq.ft.) have been measured as heat fluxes across the motor wall.

### Important Parameters

**Performance Parameters.** Parameters of interest in determining the performance of rocket motors are given in the following list:

$$c = \frac{F}{m}$$

$$I_{sp} = \frac{c}{g_0} = \frac{F}{mg_0} = \frac{F}{w}$$

$$c_{th} = \left\{ \frac{\sqrt{\frac{RT_e}{M\gamma}}}{\left( \frac{2}{\gamma+1} \right) \frac{\gamma+1}{2(\gamma-1)}} \right\} \times \left\{ 2 \sqrt{\left( \frac{\gamma^2}{\gamma^2-1} \right) \left( \frac{2}{\gamma+1} \right)^{\frac{2}{\gamma-1}}} \sqrt{1 - \left( \frac{p_e}{p_c} \right)^{\frac{\gamma-1}{\gamma}}} \right\}$$

$$= c^*_{th} \times C_F$$

$$c^* = \frac{p_e A_t}{m} = K(\gamma) \sqrt{\frac{T_e}{M}}$$

The effective exhaust velocity  $c$  approximates the actual velocity of efflux from the nozzle; the higher the exhaust velocity, the larger the thrust  $F$  developed from a given influx of propellant  $m$ . Similar to  $c$  is the specific impulse  $I_{sp}$ , which algebraically is merely the quotient of  $c$  divided by the acceleration of gravity  $g_0$ , and hence is also the quotient of the thrust  $F$  divided by the weight rate of flow of propellant  $w$ . Thus  $I_{sp}$  is numerically equal to the thrust obtained from a propellant flow rate of 1 lb./sec. The nozzle thrust coefficient  $C_F$  has little to do with combustion, since it is dependent only upon the pressure ratio  $p_e/p_c$  (between chamber and nozzle exhaust) and the effective value of the ratio of specific heats  $\gamma$  for the combustion gases. Hence it is usually considered as a sort of nozzle efficiency factor. The so-called characteristic velocity  $c^*$  is algebraically equal to the quotient of  $c$  divided by  $C_F$ , and thus should be dependent only upon combustion conditions in the rocket chamber. It is seen that its value is theoretically proportional to the square root of the ratio of the flame temperature  $T_e$  to the average molecular weight  $M$  of the combustion gases. Hence, if the flame temperature is limited either by design conditions or by thermochemical considerations, it will be noted that use of a hydrogen-rich fuel which will produce

combustion gases of low average molecular weight is desirable (2).

**Other Parameters.** Other pertinent parameters are the mixture ratio  $r$  (defined as the ratio of the weight flow of oxidizer to the weight flow of fuel), the chamber pressure  $p_e$  and the flame temperature  $T_e$ . Of course,  $T_e$  is dependent upon the mixture ratio (generally the highest flame temperature is attained when  $r$  is near the stoichiometric value); to some extent  $T_e$  is also dependent upon the chamber pressure, since an increase of pressure tends to decrease the amount of energy-removing dissociations. Another important parameter, from the design standpoint, is the unitary heat flux  $q$  (in B.t.u./sq.in.) across the motor walls. If the product of the heat flux and the

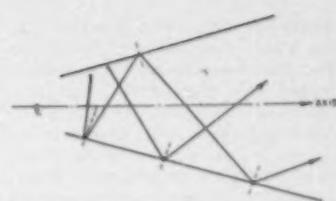


Fig. 2. Collimation of Molecular Momenta Along Nozzle Axis.

### Chemical Reactions in Rockets

**Initial Reactions.** The initial reactions in the rocket can occur either in the liquid phase or in the gas phase. In the former case, ignition often occurs spontaneously. (The Germans classified propellants of this type as hypergolic, a code word which is coming into relatively general use.) Such a reaction is that between nitric acid and aniline. For reactions of this type the chief function of the injector consists of mixing the propellant components as uniformly and intimately as possible, in order to obtain the maximum heat release from the liquid-phase reactions.

When the initial reactions occur in the gas phase, spontaneous reactions are almost never encountered; then some auxiliary source of energy, such as a spark or a pyrotechnic device, must be used to initiate combustion. For example, the German *V-2*, which employs alcohol and liquid oxygen as the propellant, uses as an igniter a pyrotechnic

inner surface area of the motor is greater than the allowable heat capacity of the propellant components, no possibility for regenerative cooling exists. The discussion of the often contradictory design requirements of sufficient cooling and sufficient strength is not within the scope of this paper.

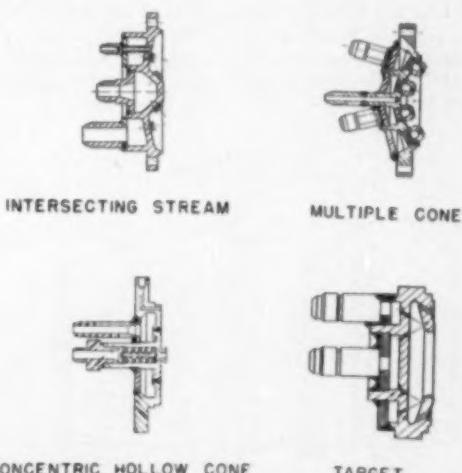


Fig. 3. Four General Types of Injector for Use with Liquid-propellant Rocket Motor.

device similar to the old Fourth of July pin wheel. Atomization of the propellant components, with its consequent promotion of vaporization, seems to be necessary in the majority of gaseous-phase ignitions in order to decrease the amount of precombustion volume. However, mixing of the propellant components is still necessary, and the evidence as to whether mixing or atomization is the most important among the several functions of the injector is as yet inconclusive in this case. The following tabulation presents a schematic plan of the possible steps in the two types of combustion processes; the proper injector design will facilitate the completion of the first two or three steps outlined.

**Spontaneous Bipropellant**

- Liquid-phase mixing
- ↓
- Liquid-phase reaction releasing heat
- ↓
- Vaporization and mixing in gas phase
- ↓
- Additional reaction
- ↓
- Final approach to equilibrium

the protruding buttons; mixing of the propellant components is in this case a secondary aim. These examples illustrate the contradiction usually encountered in the design of injectors; if mixing is to be emphasized, atomization is perhaps neglected, and vice versa.

The preceding discussion concerning initial chemical reactions in rockets has at least indicated that the basic problems of combustion related to injector design are (1) determination of the type and speed of the initial reactions and (2) influence of external factors (temperature, turbulence, etc.) on these reaction speeds.

**Reactions in Chamber.** Kinetic processes of the actual combustion in the

**Nonspontaneous Bipropellant**

- Atomization
- ↓
- Vaporization by heat transfer and gas-phase mixing
- ↓
- Breakdown of oxidizer and fuel by heat
- ↓
- Reaction and heat release
- ↓
- Final approach to equilibrium

Some injector types which have been used at the Jet Propulsion Laboratory of the California Institute of Technology are shown in Figure 3. The intersecting-stream type was designed to give good mixing of the propellant components in the liquid phase; the concentric hollow-cone type is a modification designed to increase the circumferential uniformity of the mixing process; and the target type imparts turbulence (and hence better mixing) to the products of the first liquid-phase reactions. The multiple-cone type yields relatively well-atomized conical sprays from each of

chamber are almost completely unknown at present; only indirect evidence, obtained by empirical correlation of certain types of test data, is now available. In the chamber occur the chemical reactions between the gaseous fragments of the oxidizer and fuel molecules and other intermediate products. These reactions tend toward establishment of chemical equilibrium at the prevailing pressure and temperature. Any device which promotes the establishment of equilibrium in a shorter time or in a smaller chamber volume will generally prove desirable.

The basic knowledge desired concerning combustion in the rocket chamber is the point-to-point variation in flame temperature, density, and composition of the combustion gases. Lately some American laboratories have begun to attack these problems; during the recent war some German laboratories also conducted investigations in this field. But the German results were not complete, and the American results are only preliminary; therefore a discussion of the data will not be attempted here.

Since the basic thermodynamic parameters must generally be considered unknown as yet, the closeness of approach to theoretical conditions is estimated in most cases by the value of the so-called specific characteristics velocity  $c^*/c_{th}^*$ , sometimes erroneously known as the combustion efficiency. (The theoretical characteristic velocity  $c_{th}^*$  is calculated on the assumption that thermochemical equilibrium has been established at the entrance to the nozzle). This parameter can thus be made to serve as a discriminant for injector and chamber modifications; in fact, both the proper size and proper shape of the rocket chamber can be determined empirically by its use.

The chamber shape generally chosen has been the cylindrical, since it is more easily fabricated than is the spherical shape. But general agreement regarding the proper size parameter has by no means been reached. The Germans believed intuitively that the proper size parameter was the chamber length  $L_c$ ; after the proper length was established, whatever the scale of thrust, only the appropriate changes in diameter should be necessary. Unfortunately the experimental facts did not correspond to this simple picture; recent American data indicate that the optimal length  $L_c$  is related to the ratio of the nozzle throat diameter to the chamber diameter. Other size parameters often used include the relative volume  $V_B$ , defined as the volume necessary for the satisfactory combustion of a unitary weight flow of propellant, and the characteristic length  $L^*$ , defined as the ratio of the chamber volume to the nozzle throat area. The parameter  $L^*$  can be shown to be directly proportional to the average time spent by a fuel particle in the chamber (and hence the time available for the establishment of chemical equilibrium), if it is assumed that there are no turbulent eddies in the chamber. The Germans found that the use of an empirically established  $V_B$  yielded the most nearly consistent data when chamber pressures or thrusts were varied. All

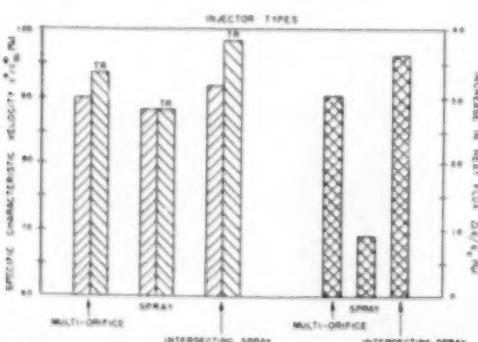


Fig. 4. Effect of Turbulence Ring on Performance and Heat Transfer.

these parameters are now in use, although none can as yet be adequately justified on a theoretical basis. Actually, the artificial production of extra turbulence (a factor ignored in the setting up of the size parameter  $L^*$ ) will often aid the combustion, since it causes additional mixing of the gaseous combustion products and lengthens the effective time spent in the chamber by fuel particles. Figure 4 illustrates the increases of performance obtained by the insertion of a square turbulence ring midway down the length of an aniline-nitric acid combustion chamber. Three injectors, two of the mixing type and one of the atomizing type, were used in these tests. It is noteworthy that up to 98% of the theoretical value of  $c^*$  was attained in the best case, but these typical performance increases were also accompanied by marked increases in heat fluxes. The latter phenomenon seemed to be due mainly to the decrease in thickness of the insulating boundary layer because of the increased turbulence of the main stream.

**Reactions in the Nozzle.** It is still a debatable point whether chemical reactions are going on in the nozzle of the motor. As mentioned earlier, in the thermochemical calculations it has always been assumed that complete thermochemical equilibrium has been set up at the flow station corresponding to the entrance of the nozzle. In practice, the research engineer generally tries to achieve this ideal, if maximum performance is desired. The phenomenon of combustion continuing throughout expansion has never been systematically investigated, probably because of the thermodynamic precept that more useful work can be obtained from heat released at higher pressure levels. However, two concepts of the expansion process are now under preliminary experimental attack. The frozen flow or, more properly, the constant-composition concept assumes that no further reaction occurs during the expansion because of the extremely short times (of the order of  $10^{-4}$  sec.) which the gases spend in the nozzle. On the other hand, the equilibrium-composition concept assumes that the gases follow thermochemical equilibrium throughout the expansion process, so that partial reassociation of the dissociated products present in the chamber occurs in the nozzle (with a consequent energy release). Hence, this second concept yields a theoretical exhaust velocity higher than that predicted by the concept of constant composition.

A theoretical treatment of one of the

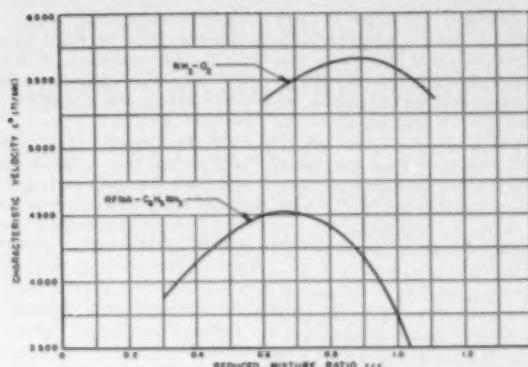


Fig. 5. Comparison of Carbonaceous and Non-Carbonaceous Fuels:  
I, Absolute Performance.

most important energy-absorbing dissociations (1), that of molecular hydrogen, indicates that this reaction is almost certainly in equilibrium throughout the expansion process. However, an experimental investigation of the pressure

levels in the nozzle of a small hydrogen-oxygen motor seems to indicate that the constant-composition concept holds, at least for the particular motor used. (Since the exhaust velocities obtained from a given propellant system under

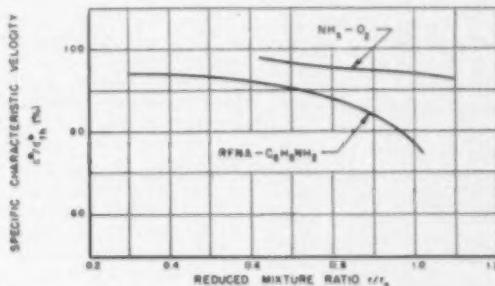


Fig. 6. Comparison of Carbonaceous and Non-Carbonaceous Fuels:  
II, Relative Performance.

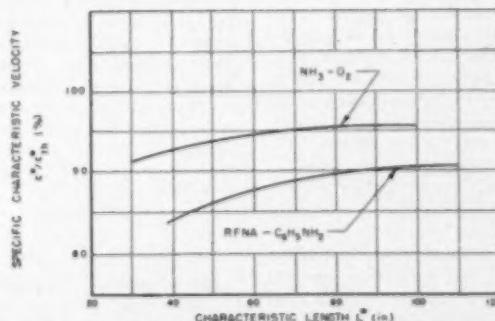


Fig. 7. Comparison of Carbonaceous and Non-Carbonaceous Fuels:  
III, Required Chamber Volume.

the same pressure conditions are approximately constant, whatever the thrust of the motor, it is evident that the time spent by the gases in the nozzle, and hence the time available for the maintenance of equilibrium, is directly proportional to the nozzle length, and thus is dependent upon the thrust of the motor.) Other conflicting data are also available, but will not be discussed here.

An adequate theoretical treatment of the expansion phenomena is not only exceedingly complex, but at present absolutely impossible, because of the lack of the necessary high-temperature kinetic data. Direct spectroscopy and further indirect methods will be jointly used in the future to clarify the actual processes of expansion.

### Use of Noncarbonaceous Fuels

Use of noncarbon-containing fuels as propellant components for rocket motors was first proposed in this country by members of the Jet Propulsion Laboratory late in 1944. Examination of the predicted and experimental advantages of this type of system should serve as a clarifying example of the discussion given here concerning chemical influences on rocket design and performance.

Though noncarbonaceous fuels do not in general have heats of combustion as high as do carbonaceous fuels, nevertheless higher characteristic velocities at lower flame temperature are attained often by use of noncarbonaceous fuels, because of the lower average molecular weights of their combustion products (see Performance Parameters). Since the phenomenon of dissociation limits the maximum flame temperatures obtainable, and the preponderant product of carbon combustion at high temperatures ( $>3000^{\circ}$  K.) is carbon monoxide, with a relatively low heat of reaction, it is evident that the low-molecular-weight products of partial hydrogen combustion are to be desired.

Another advantage which could be postulated for noncarbon systems is that their reaction kinetics should be simpler than in the case of hydrocarbon combustion, thus making possible the use of smaller (and hence lighter) motors. Similarly, the phenomenon of reassociation (partial or complete) during expansion in the nozzle should be obtained more easily with noncarbon systems; thus at least some of the thermal energy lost in the chamber due to dissociation could be made available for conversion to exhaust velocity.

Experimental verifications of these predictions may be illustrated by comparing the systems  $C_6H_5NH_2$ -RFNA and  $NH_3-O_2$ , which have the same maximum theoretical flame temperature (within  $20^{\circ}$  K.). Figure 5, which shows the variation of  $c^*$  with reduced mixture ratio for the two systems, illustrates that the noncarbon system yields performances approximately 20% better than those of the carbonaceous. (The reduced mixture ratio  $r/r_s$  is the quotient of the mixture ratio in question divided by the stoichiometric mixture ratio. It is a convenient concept for comparing propellants which require markedly different amounts of oxidizer.) Figures 6 and 7 illustrate the simpler reaction kinetics of the noncarbonaceous combination: the former shows the closer approach to theoretical conditions; the latter shows that smaller motors may be used with noncarbonaceous systems, for a desired closeness of approach to the theoretical performance.

### Conclusion

To summarize, the knowledge of the course of combustion phenomena in liquid-propellant rocket motors would be greatly extended if accurate point-to-point gas temperatures, densities, and compositions could be experimentally determined. Further kinetic studies at high temperatures should also be made in order to interpret more easily the temperature and composition data. Meanwhile, we shall have to rely on the indirect methods and empirical correlations already discussed to enable us to build injectors, chambers, and nozzles which are optimum from the standpoint of combustion efficiency.

### Acknowledgment

My thanks are due to my colleagues at the Jet Propulsion Laboratory, who supplied some data referred to in this paper. I also wish to acknowledge the advice and assistance of Dr. Louis G. Dunn and Dr. Martin Summerfield, who kept in touch with all the experimental programs the results of which are here mentioned.

### Notation

$A_t$  = nozzle throat area, sq.in.

$c$  = effective exhaust velocity, ft./sec.

$c_{th}$  = theoretical exhaust velocity, ft./sec.

$c^*$  = experimental characteristic velocity, ft./sec.

$c_{th}^*$  = theoretical characteristic velocity, ft./sec.

$C_p$  = nozzle thrust coefficient

$F$  = thrust developed by rocket, lb.

$g_0$  = standard acceleration of gravity, ft./sec.<sup>2</sup>

$I_{sp}$  = specific impulse obtained from rocket propellant, lb.(sec.)/(lb.)

$L_c$  = length of rocket chamber, in.

$L^*$  = characteristic length of rocket motor, in.

$m$  = mass flow of propellant, slugs/sec.

$M$  = average molecular weight of combustion products, lb./mole

$P_e$  = pressure at nozzle exit, lb./sq.in.abs.

$P_r$  = pressure in rocket chamber, lb./sq.in.abs.

$q_o$  = original heat flux across rocket motor walls, B.t.u./sq.in.(sec.)

$\Delta q$  = increase in heat flux across rocket motor walls, B.t.u./sq.in.(sec.)

$r$  = mixture ratio = wt. oxidizer/wt. fuel

$r_s$  = stoichiometric mixture ratio ft.lb./mole

$R$  = universal gas constant, ft.lb./mole( $^{\circ}$  R.)

RFNA = abbreviation for red fuming nitric acid

$T_c$  = adiabatic flame temperature,  $^{\circ}$  R.

$V_R$  = relative volume of rocket chamber, cu.in./lb.sec.

$w$  = flow of propellant, lb./sec.

$\gamma$  = ratio of specific heats

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# TURBULENT DIFFUSION IN FIXED BEDS OF PACKED SOLIDS

ROBERT A. BERNARD† and RICHARD H. WILHELM

Princeton University, Princeton, New Jersey

This study concerns turbulent diffusion in beds of packed solids through which a fluid is flowing. The work is of interest in the technology of catalytic reactors and in packed-tube heaters, coolers, mixers and absorbers.

Liquid phase experiments were performed with a methylene blue solution diffusing from a point source into water flowing through a bed of packed solids and gas phase experiments with carbon dioxide diffusing into an air stream in such a bed. The basic differential equation was solved for the special case when the tube wall provides a boundary condition. Aqueous experiments were performed in a 2-in. tube and included the following particles: 1, 3, 5, 8 mm. spheres;  $3/16 \times 3/16$  in. and  $3/4 \times 3/4$  in. cylinders;  $3/4$  in. cubes; 10-14 mesh granules; and a mixture of 1 and 3 mm. spheres. Gaseous experiments were performed in an 8-in. tube with  $3/8$ -in. spheres. Pertinent correlating parameters were modified Peclet Group,  $D_p u/E$ , and modified Reynolds number,  $D_p V_{\rho p}/\mu$ . The experimental range of the modified Reynolds number was from 5 to 2,400. Pressure-drop data also were recorded and correlated. A lower Reynolds limit for the stability of turbulent diffusion because of interference by gross wall-generated eddies was observed and is discussed.

In recent years, processes involving heat and material transfer within beds of packed solids have gained an important place in the repertoire of the chemical engineer. One well-known example is that of fixed-bed catalytic reactor design. Regardless of the design procedure it is necessary to be able to predict accurately the magnitudes of the various heat-transfer resistances within the bed. Under conditions obtaining in industrial practice, turbulent transfer within the fluid interstices of the bed often represents the path of least resistance between particles in the bed and the wall of the reactor. Therefore, actual measurements of interstitial turbulent diffusion coefficients should be of interest to the industrial designer. The work upon which this paper is based was undertaken as a logical adjunct to a catalytic reactor design program underway in this laboratory.

Interstitial turbulent heat-transfer mechanisms are of importance also in steady-state and nonsteady-state heating processes in packed tubes. The supply

of regeneration heat in an adsorbent bed by means of heating jackets at the retaining walls is an example. Another example is heating a gas or superheating a vapor by passage through a heated, packed tube. The latter heat-transfer arrangement has been studied by Chilton and Colburn (3) and more recently by Leva (8).

In general, temperature gradients within a packed reactor, heater or adsorbent bed will be accompanied by concentration gradients. Therefore, a complete solution to any packed-bed design problem should also include the effect of turbulent material transfer in both the longitudinal and transverse directions. To the present time, design methods have made no provision for the inclusion of the effect of mass transfer, due to the mathematical complications involved.

## Theory

Turbulent motion can arise in several different ways. In the case of a fluid flowing around a bluff object such as a cylinder or sphere, a boundary layer is formed next to the surface of the object, the fluid velocity varying in this layer

from zero at the surface to the main stream velocity at the outer edge of the boundary layer. At the rear of the object, the boundary layer encounters a region in which the static pressure increases in the direction of motion of the layer, which is thus opposing an adverse pressure gradient. At Reynolds numbers greater than a certain limiting value, the boundary layer cannot penetrate the adverse pressure region to the rearmost point of the object, and separation of the boundary layer from the rear surface of the object takes place before the rearmost point is reached. The free boundary layer tends to curl up on itself, forming a stationary eddy behind the object. As the Reynolds number is increased further, eddies are continuously shed and reformed at the rear of the object, and the freed eddies maintain their form for some distance downstream, finally breaking up into the irregular eddying motion of true turbulence. Finally, at still higher values of Reynolds number, the boundary layer itself becomes turbulent before it leaves the surface. In other words, at some point in its trip around the surface, the increase in the ratio of the inertial forces to the shearing forces within the boundary layer causes steady motion to become an unstable state, and the irregular eddying of turbulence takes over. In this case the wake behind the object is everywhere turbulent and no trace of regular motion can be found in it.

With regard to turbulence within a straight pipe or next to a flat plate, separation of the boundary layer under the influence of an adverse pressure gradient does not enter the picture. Here, the turbulence is generated within the boundary layer itself, as in the case of the bluff object at high velocities. The turbulence thus generated at the wall of a pipe replenishes the energy of the turbulent core, which is being continuously dissipated by energy interchange within the core. A third mode

† Present address: DuPont Company, Wilmington, Del.

of turbulence generation is that encountered when a jet of fluid is discharged into a relatively quiescent fluid body. The turbulence originating at the boundary of the jet spreads inward toward the center of the jet and outward into the surrounding fluid, finally converting the jet into a completely turbulent wake.

Dryden (4) has provided a discussion of the statistical nature of turbulence. As molecular motion may be characterized by mean free path and mean molecular velocity so may turbulent motion be described in terms of the analogous parameters, scale and intensity of turbulence. In making this analogy the discrete nature of molecular motion on the one hand, and the motion in fluid turbulence by random but continuous movements on the other, necessitate differences in detailed treatment. The molecular diffusion coefficient is proportional to the product of mean free path and mean molecular velocity; the eddy diffusion coefficient, to the product of scale and intensity of turbulence.

In principle, two experimental procedures may be used to determine turbulent diffusion coefficients. By means of a statistical treatment of hot wire anemometer measurements the scale and intensity of the turbulence may be determined. Then, if the constant of proportionality has been determined by direct diffusion measurements in a given field, the diffusion coefficient for a similar field can be estimated from this value and the measured values of the turbulence parameters. However, complete geometrical similarity is seldom encountered, so that this method usually gives only a rough approximation to the correct value of the diffusion coefficient. The second procedure is the direct measurement of the rate of diffusion and concentration gradients of a foreign component introduced into the system. The latter procedure was the one used in the present work.

Since turbulent heat transfer and turbulent material transfer take place by the same mechanism, the eddy mass diffusivity and the eddy thermal diffusivity are assumed to be one and the same quantity. The following are the parallel rate equations for the two mechanisms:

#### Heat transfer:

$$q = -(k + \mu E) \frac{dt}{dy} \quad (1)$$

#### Mass transfer:

$$N = -(D + E) \frac{dc}{dy} \quad (2)$$

In the above,  $k$  and  $D$  represent molecular thermal and mass-transfer coefficients, respectively.  $E$  is the eddy diffusivity and the product,  $\mu E$ , is the

eddy thermal conductivity. Thus, eddy diffusion experiments may be used to evaluate  $E$  and the results may be applied to problems of turbulent heat transfer under conditions of similarity.

Previous measurements of turbulent diffusion were performed in unpacked conduits in which turbulence is generated at the container wall. In 1939 Towle and Sherwood (9) reported the results of an investigation of mass transfer in the central portion of turbulent air streams in two sizes of round pipe. A tracer gas was released into the center of an air stream, and concentration traverses were made at several downstream cross sections. Carbon dioxide and hydrogen were used as tracer gases. Since the turbulence in the central part of a pipe is known to be approximately isotropic and uniform, Towle and Sherwood applied an equation which had been previously derived by Wilson (12) for the diffusion of heat from a point source into a flowing stream by means of molecular conduction. The eddy diffusivity was found to be almost directly proportional to the Reynolds number, and the results for hydrogen and carbon dioxide fell on the same line, indicating that the eddy diffusivity was always great enough to mask the differences in the molecular conductivity.

A second paper, by Woertz and Sherwood (13), described experiments in the diffusion of water vapor across a gas stream flowing in a vertical, rectangular duct. The water was allowed to flow down one wall of the duct in a film, and the water vapor that diffused across was absorbed in a film of calcium chloride brine which flowed down the opposite wall. Concentration traverses were made. Air, carbon dioxide, and helium were used as main gas stream materials. By the use of mathematical manipulations based on the mixing length theories of Prandtl and von Karman, the authors arrived at an equation relating the eddy diffusivity, the integral average velocity, the half-width of the conduit, and the friction factor. The equation fitted the experimental data well.

In a short paper, Kalinske and Pien (6) described eddy diffusion measurements in turbulent water streams flowing in rectangular open channels. Hydrochloric acid in ethanol was used as the tracer. The method used was the same as that of Towle and Sherwood, i.e., the tracer was injected into the center of the flowing stream, and concentration traverses were taken at various downstream cross sections. Results of this work tend to support Taylor's theory of diffusion by continuous movements.

No previous eddy diffusion study has been reported for turbulence generated by a fixed packing.

**Mathematical.** In planning the present experimental work it was recognized that direct measurement of the parameters of turbulence within the interstices of a packed bed would be difficult. Furthermore, translation of these measurements into values of the eddy diffusion coefficient would lead to rough approximations at best. Therefore, it was decided to use a direct method which would yield an average value of the eddy diffusivity. The method of Towle and Sherwood (9) just outlined, was chosen. A choice also had to be made between the use of heat and of a tracer substance in the diffusion studies. Although the release of heat from a point source within a bed and the determination of downstream temperature profiles are simple and direct procedures, the problem of interparticulate heat conduction at points of contact within the bed would have caused serious mathematical difficulties in the analysis of experimental data. Therefore, a tracer substance was given preference as the diffusion material.

At steady state, the partial differential equation in cylindrical coordinates for diffusion-convection is:

$$E_t [\frac{\partial^2 C}{\partial r^2} + \frac{1}{r} (\frac{\partial C}{\partial r}) + \frac{\partial^2 C}{\partial z^2}] - u \frac{\partial C}{\partial z} = 0 \quad (3)$$

$E_t$  is the point value of the total diffusivity, defined through Equation (2) as the sum of molecular and turbulent components,  $D + E$ .  $C$  is the concentration of the tracer substance,  $r$  is the radial coordinate, measured from the axis of the tube and  $z$  is the longitudinal coordinate, measured from the point of injection. The first term in the equation represents motion of the tracer because of diffusion and the second, because of convection by the fluid stream. No angular derivative is included in the first term, since the system has radial symmetry.

If Equation (3) is divided by  $E$  the following equation containing only a single constant,  $a$ , is obtained:

$$\frac{\partial^2 C}{\partial r^2} + \frac{1}{r} (\frac{\partial C}{\partial r}) + \frac{\partial^2 C}{\partial z^2} - a (\frac{\partial C}{\partial z}) = 0 \quad (4)$$

where:

$$a = u/E_t \quad (5)$$

In solutions of Equation (4) the assumption is made that  $a$  is everywhere constant. It is the value of this ratio that is evaluated experimentally rather than the value of  $E_t$ . Auxiliary measurements of fluid velocity (or assumptions regarding its distribution) must be made to evaluate or estimate  $E_t$  as an individual constant. In considering solutions for Equation (4) the presence of packing may be disregarded for the moment.

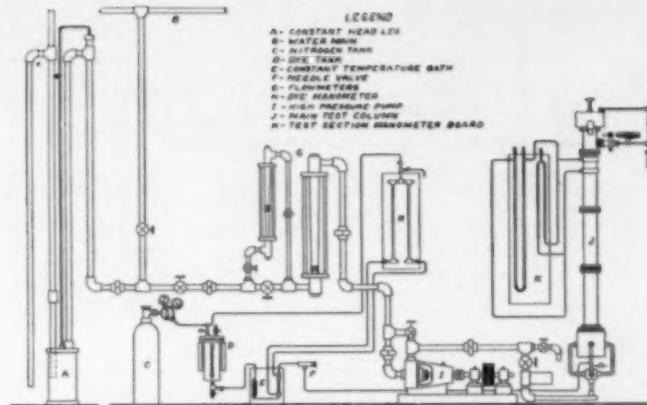


Fig. 1. Equipment Arrangement for Measuring Eddy Diffusivity in Water Flowing Through a Bed of Packed Solids.

In certain experiments of this work diffusion was limited to the central core of the tube and in others, diffusion proceeded until the tube wall boundary became important in stopping radial diffusive motion. The solution of Equation (4) with no wall boundary has been provided by Wilson (10). For the case of a tube wall boundary condition a new solution had to be made to permit evaluation of data.

*Solution With No Wall Boundary.* The Wilson equation was derived originally for diffusion of heat from a point source into a flowing stream of infinite extent. Written for its mass-transfer analogy in which a tracer material is released at a point, the equation is as follows:

$$C = (Q/4\pi E_t \sigma) e^{-\sigma^2/4t} \quad (6)$$

The equation as written has included a simplification which is possible when  $\sigma/\tau > 5$ , a condition encountered in present experiments. It is convenient to measure,  $Q$ , the rate of tracer material injection through the mixed average effluent concentration  $C_A$ . Thus:

$$Q = C_A V_0 \pi \sigma^2 \quad (7)$$

where  $V_0$  is the integral average fluid velocity based upon the empty tube and the letter,  $\sigma$ , is the tube radius.

Substituting Equation (7) in (6) we obtain:

$$C/C_A = (\sigma^2/4\pi) e^{\sigma^2/4t} \quad (8)$$

$\sigma'$  in the coefficient of the equation is primed to indicate that it is defined in terms of an integral average velocity rather than point velocity. For this reason, but also if  $\sigma$  is not constant and if Equation (4) has limitations in theory, we may expect that  $\sigma'$  and  $\sigma$  will not

have identical values as determined through experiment. Small differences between the two are, in fact, obtained.

*Solution With Wall Boundary.* Boundary conditions for this case are:

$$\sigma = +\infty \quad C = C_A$$

$$\sigma = -\infty \quad C = 0$$

$$\sigma = a \quad \frac{\partial C}{\partial \sigma} = 0$$

The solution will be based upon Lord Kelvin's method \* of point sources. This method starts with a nonsteady-state equation and extends it to include the effect of convective flow.

The effect in the point  $(r, 0, z)$  at time,  $t$ , of an instantaneous amount of tracer material,  $q$ , applied at time,  $t = 0$  and at point  $(0, 0, 0)$  with boundary conditions as given here, can be written directly for its mass-transfer analog from Carslaw and Jaeger's (2) equation for heat transfer. The resulting equation is:

$$C/q = \frac{e^{-\sigma^2/4E_t t}}{2\pi a^2 (\pi E_t t)^{1/2}} \sum_{n=0}^{\infty} e^{-E_t \beta_n \sigma t} \cdot \frac{J_0(\beta_n r)}{J_0(\beta_n a)} \quad (9)$$

with  $J_1(\beta_n a) = 0$ .  $\beta_0, \beta_1, \beta_2, \dots$  are the positive roots, in ascending order, of  $J_1$ , the Bessel function of the first order, first kind.

The effect of the motion of the fluid along the point source is considered by

\* The method was suggested by a reviewer of this paper, Dr. A. Klinkenberg, Royal Dutch-Shell Group, The Hague, Holland, as being briefer and more direct for purposes of publication than that presented originally. The final solutions are identical.

replacing  $z$  with  $z-\sigma t$ . Further, if the variables,  $p$  and  $q$  are defined:

$$p^2 = (u^2/4E_t + T_t \beta_n^2) \quad q^2 = \sigma^2/4E_t$$

substitutions in (9) will lead to the following equation:

$$C/q = \frac{e^{qa/2}}{2\pi a^2 (\pi E_t t)^{1/2}} \sum_{n=0}^{\infty} e^{-q^2/t + p^2} \cdot \frac{J_0(\beta_n r)}{J_0(\beta_n a)} \quad (10)$$

If a succession of concentrations of tracer in the amount,  $q$ , are applied at time intervals, the concentration  $C$  will be the sum of all concentration contributions arriving at  $(r, 0, z)$  because of the successive actions at the origin. If the succession of applications is made continuous by forming a stream of tracer material,  $Q$ , at the origin then the effective concentration at a given length and radius position will be the continuous sum, or integral of Equation (10) from  $t = 0$  to  $t = \infty$ . Thus for a flow system:

$$C/Q = \frac{e^{qa/2}}{2\pi a^2 (\pi E_t)^{1/2}} \sum_{n=0}^{\infty} \frac{J_0(\beta_n r)}{J_0(\beta_n a)} \int_0^{\infty} e^{-[q^2/t + p^2]} \cdot \frac{dt}{t^{1/2}} \quad (11)$$

The integral is known (1):

$$\int_0^{\infty} e^{-[q^2/t + p^2]} \cdot \frac{dt}{t^{1/2}} = \frac{\pi^{1/2}}{p} e^{-2pq} \quad (12)$$

Performing the indicated substitution and including also the definition of  $Q$  through Equation (7) the final solution in the desired form for insertion of experimental data is obtained:

$$C/C_A = a' \sum_{n=0}^{\infty} \frac{e^{-[a - (a^2 + 4\beta_n^2)^{1/2}]a/2}}{(a^2 + 4\beta_n^2)^{1/2}} \cdot \frac{J_0(\beta_n r)}{J_0(\beta_n a)} \quad (13)$$

A modification must be introduced now in order to take into account the presence of packing within the conduit. It can be shown that the fractional free area of a cross section within the bed,  $A_p$ , is equal to the fraction voids,  $a$ . Since material can be transported only across a free area,  $E_t$  must be replaced by  $E_t a$  and by  $u a$ .  $a = u s/E_t = u/E_t$  which does not contain  $a$ . However, in correlating data the average velocity,  $V_0$ , based upon the empty cross section rather than the interstitial velocity is

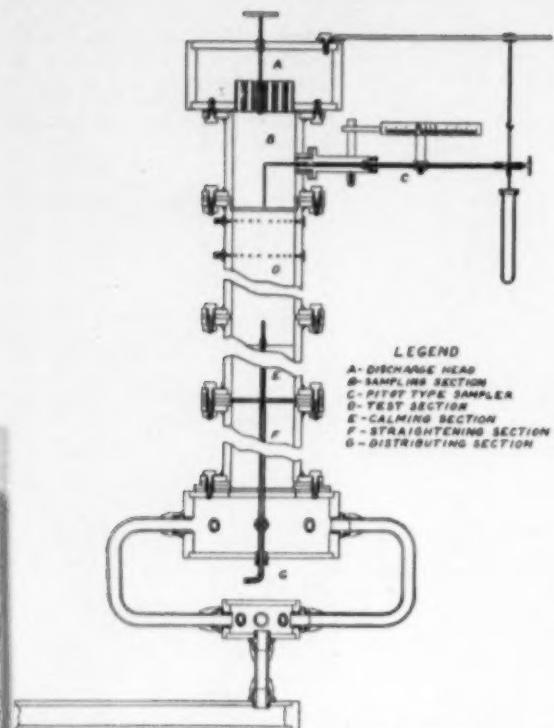


Fig. 2. 2-Inch Column for Measuring Eddy Diffusivity in Water Flowing Through a Bed of Packed Solids.

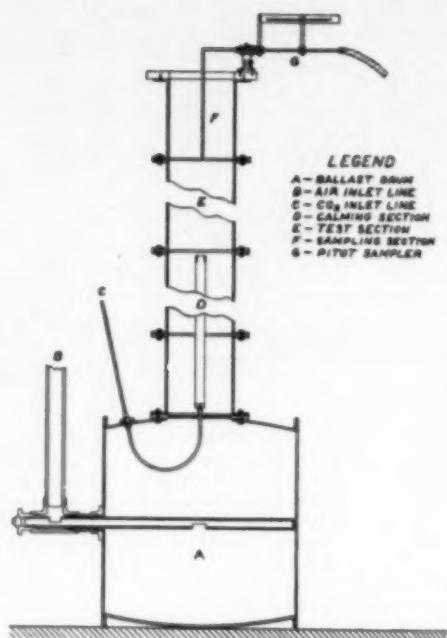


Fig. 3. 8-Inch Column for Measuring Eddy Diffusivity in Air Flowing Through a Bed of Packed Solids.

used. If  $u$  is assumed constant over the cross section, then  $n = V_u/\epsilon$  and  $a = V_u/uE_t$ . If molecular and turbulent effects are to be segregated through  $E_t = E + D$ , the relation

$$\frac{E}{u} = \frac{1}{a} - \frac{4D}{V_u}$$

is obtained. Therefore, in order to compute the value of  $u/E$  from the experimental  $a$ , knowing  $V_u$  and  $D$ , the value of  $\epsilon$  must be known.

It was previously noted that  $a'$  might differ from  $a$  for a number of reasons, but particularly because  $a$  is based upon point conditions and  $a'$  upon integral average conditions over the tube cross sections. It is noted, furthermore, that  $a'$  is a multiplying coefficient in both Equations (8) and (13) which does not affect the shape of the  $(C/C_A) - r$  curve. It is convenient to let  $a' = Ba$  where  $B$  is a constant. If  $B = 1$ , the integral average concentration ratio  $(C/C_A)_{av}$  will also be unity. Therefore  $(C/C_A)_{av} = B$ , and  $B$  can be evaluated by means of a graphical integration of the experimental data.

$$B = (C/C_A)_{av} = (2/a^2) \int_0^a (C/C_A) r dr \quad (14)$$

Under the conditions obtaining in this investigation, it can be shown that the eddy diffusivity in the longitudinal direction has little effect on the shape of the concentration profile, and the quantity actually measured is  $E_t$  in the radial direction. It is conceivable that in a packed bed, the longitudinal and radial values of  $E_t$  might be somewhat different. However, the measurement of  $E_t$  in the longitudinal direction, separate from the radial  $E_t$ , would be a very difficult problem.

### Experimental

In planning experimental work it seemed desirable to investigate both air and water systems, representing widely different physical properties. The size of equipment for each system was influenced by the analytical techniques that could be brought to bear. Methylene blue as the tracer material in the water experiments permitted high analytical accuracy with small samples in a photoelectric colorimeter and the use of a small apparatus was possible. With regard to the air system, a small apparatus would have required the use of a micro or semimicro method of analysis. With a larger apparatus, the tracer substance is restricted to the few gases

readily available in large quantities, relatively nonpoisonous, and amenable to simple analysis. Carbon dioxide was finally chosen as the tracer, hydrogen having been rejected because of explosion hazard, and because its high molecular diffusivity would have reduced the accuracy of the experimental measurements. The method of analysis by thermal conductivity meter was chosen, because it is a clean, rapid and continuous procedure. In practice, the water apparatus was found to be easier and more economical to handle than the air apparatus, especially from the standpoint of testing a number of different packing sizes and shapes. Therefore, it was decided to use the former for the major portion of the experimental work, after which the results from both apparatuses could be compared in order to detect any discrepancies between the gas and liquid systems.

**Apparatus.** Figure 1 shows the water apparatus. The double-section, constant head leg,  $A$ , supplied a constant feed pressure to the suction side of the pump. The two rotameters,  $G$ , covered a flow range of 0.1-13.7 gal./min. Nitrogen tank  $C$  supplied gas pressure to dye storage tank  $D$ , in order to force the dye into the bed against the back pressure within the latter. The dye solution contained about 4 g. of dye/l. of solution, and the dye rate was controlled by

valve *F*, which has a long tapering seat, thereby facilitating control at the low flows used (as low as 1 cc./min. in some runs). Manometer *H* was used for indicating constancy of flow of the dye solution. High pressure pump *I* is a Worthington type *TF* regenerative turbine pump, driven by a 3 hp., 3450 rev./min. induction motor, and capable of delivering 10 gal./min. at a pressure of about 150 lb./sq.in. A filter was incorporated in the line between the pump and the main test column in order to prevent rust and other debris from reaching the latter.

Figure 2 is a section drawing of the main test column. The water entered a small header, from which it proceeded through eight radial arms to distributing section *G*. This arrangement gave as symmetrical a water distribution as possible. Straightening section *F* was packed with 3-mm. glass tubing which broke up any large eddies generated in *G*. At the base of calming section *E* a finely perforated packing support plate, covered with 70-mesh screen, was placed. The dye inlet line entered the column through the bottom of *G*, and penetrated the support plate, extending along the column axis to the upper end of *E*. This injector tube was made of 0.128 in. O.D. stainless steel tubing, the last 3 in. portion of which was reduced to 3/32 in. O.D. It was held coaxial with the calming section by means of a three-armed spider of fine wire. As shown, test section *D* was equipped with two piezometer rings spaced exactly 3 in. apart, the upper ring being approximately 1 in. from the top of *D*. These rings were connected to the manometers on board *K* (Fig. 1), so that the pressure drop between the rings could be measured.

In operation, both *D* and *E* were completely packed with the packing which was to be tested. A special packing hold-down grid, made by milling narrow grooves at right angles to one another in opposite sides of a brass disc, was placed at the top of *D*. The pitot tube part of sampler *C* was made of 1/16 in. O.D. brass tubing, and the leg parallel to the axis of the column was 2 in. long. As shown, the sample fluid discharged through a miniature needle valve into a 10-cc. test tube. The bottom of discharge head *A* was fitted with a number of short, flow straightener tubes, which prevented the flow pattern in the sampling section from being affected by the overflow from the discharge head, placed at right angles to the pitot traverse. The water temperature was measured by a long stem, Weston bimetallic thermometer which penetrated the top of *A*. The overflow from *A*, which is not shown on Figure 2, discharged into a length of 2 in. pipe, which was fitted with a sample catcher, so that a sample of the average effluent from the column could be drawn off. With regard to the dimensions of the apparatus, sections *B*, *D*, *E* and *F* were made of 2-in. brass pipe, and sections *A* and *G* were made of 4-in. brass pipe. *D*, *E*, and *F* were 12 in. long apiece, and *B*, *G* and *A* were 5 in., 4 in., and 3 1/2 in. long, respectively. A shorter test section, 6 in. long, also was available.

In the air apparatus, the main air stream was supplied by a Roots-type blower capable of delivering about 50 cu.ft./min. at a pressure of approximately 0.7 lb./sq.in. The air line was made of 2-in. pipe, and the flow was metered by means of a set of interchangeable orifices, with attendant manometers, and air temperature thermometer. The carbon dioxide tracer was supplied to the main column from standard 50-lb. cylinders of liquid CO<sub>2</sub>, the reducing valve being wrapped with heating wire, in order to prevent freezing of the valve. A 15-ft. bubbler leg was floated on the line so as to maintain a constant supply pressure, and the CO<sub>2</sub> stream was metered by a pair of rotameters, their combined range being 0.02-2.0 cu.ft./min. at 1 atm. and 70° F.

Figure 3 is a sectional drawing of the main column of the air apparatus. The column rested on a standard 100-gal. drum, *A*, which served as a ballast drum. Air inlet line *B* pierced the side of *A* and discharged downward at the axis of the drum, insuring a symmetrical air distribution. The main column was made of short, flanged sections of 8-in. conduit, constructed of heavy gage, galvanized steel, and bolted together. The packing was supported by a perforated plate at the bottom of calming section *D*, as before, and the CO<sub>2</sub> injector tube, which extended to the top of *D*, was made of 1-in. O.D. brass tubing. Both *D* and test section *E* were filled with packing, and sampling section *F* served as a guard to prevent stray air currents from affecting the flow pattern coming from the upper face of the packing. Pitot sampler *G* was made of 1/4-in. O.D. thin-walled brass tubing, and its tip moved across the upper face of the packing. *D* was 7 ft. long, *F* was 1 ft. long, and *E* could be varied from 1 ft.-6 in. in steps of 1 ft. *G* was connected by means of rubber tubing to a set of small rotameters (combined range 0.0005-0.05 cu.ft./min. at 1 atm. and 70° F.) which measured the sampling rate, after which the sample line connected to the thermal conductivity meter assembly.

Table 1 presents characteristics of the various packings used. Average dimensions of the various types of particles were obtained either by direct measurement (by micrometer) of at least 25 particles, or by weighing a known number of particles, determining the average weight per particle, and then employing the measured value of the particle density to calculate the average volume of a particle. Average particle density was determined in the latter cases by measuring the water displaced by a known weight of packing. The equivalent diameter *D<sub>e</sub>* for nonspherical particles is the diameter of a sphere of volume equivalent to that of an average particle. *D<sub>e</sub>/D<sub>t</sub>* is the ratio of particle to true diameter. In measuring the per cent

voids, the total amount of packing in the column was weighed, the volume occupied by this weight of packing was calculated from the measured value of packing density, and the % voids calculated from this volume and the volume of the packed section. The 3/4-in. alumina spheres were an exception, in that the % voids was determined by measuring the amount of water needed to fill the void space of a known packed volume. Figure 4 is a composite photograph of the various packings.

**Experimental Procedure.** In loading the water column, the sampling section and discharge head were removed, and the empty column was filled with water. The packing was allowed to sift down through the water, and the resulting loosely packed bed was compacted by tapping the column lightly at several evenly spaced positions, after which more packing was added and compacted, etc., until the column was filled. Then the grid and sections *A* and *B* were replaced. At low flow rates the pressure supplied by the constant head leg was sufficient to force the water through the apparatus, but at higher flow rates, the pump was used. After the water rate was adjusted to the desired value, pressure was applied to the dye tank, and the dye rate was adjusted by means of the needle valve. Theoretically, the dye injection velocity should be the same as the water velocity in the bed (according to the proportions of the apparatus, the ratio of water to dye rate should be about 1000:1) or a disturbance of the flow pattern will result, but experimentally, it was found that the ratio of the rates does not need critical adjustment, because the dye rate is such a small fraction of the total flow.

The apparatus was permitted to operate for about one-half hour before sampling was begun, in order to achieve steady-state operating conditions. Sampling velocity should not be more than 50% greater than the stream velocity, or liquid will be sucked in from regions outside the immediate neighborhood of the sampler tip. The sampling rate was estimated by a timed count of the drops emerging from the sampler valve. It was the usual practice to take a dozen samples at evenly spaced points along the pitot traverse. Corresponding samples of the average effluent were collected simultaneously, the effluent sampling rate being adjusted to give a 200-300 cc. sample in the same length of time required by the collection of the 5-8 cc. profile sample. For each traverse position, besides collecting the two samples, the readings of the water rotameter, dye manometer, and water temperature thermometer were recorded, as was the estimated sampling rate.

Samples were analyzed by means of a Fisher electrophotometer, using a red filter in order to obtain maximum sensitivity. The instrument was calibrated by measuring the per cent transmission of known dilutions of dye, a solution containing 4.00 parts of dye

TABLE I.—PACKING CHARACTERISTICS

No.	Shape of Packing	Nominal Size	Material	Packing Density g./cc.	Equip. <i>D<sub>e</sub></i> in.	<i>D<sub>e</sub>/D<sub>t</sub></i>	% Voids in Bed <i>F</i> × 100
1	spherical	1 mm.	glass	2.58	0.0266	0.8177	38.7
2	spherical	2 mm.	glass	2.23	0.133	0.064	38.6
3	spherical	5 mm.	glass	2.35	0.204	0.099	60.4
4	spherical	8 mm.	lead	11.11	0.338	0.164	42.5
5	cylindrical	2/16 × 2/16 in.	alumundum	2.24	0.219	0.106	45.0
6	cylindrical	5/16 × 5/16 in.	alumundum	2.02	0.302	0.148	41.3
7	cubical	1/4 in.	polystyrene	1.04	0.140	0.068	27.8
8	granular	10-14 mesh	crushed rock	2.63	0.025	0.0305	44.8
9	spherical	1/8 in.	alumina	—	0.461	0.0572	36.8

per million of water being used as the standard, with an equivalent concentration of 1.0. The average relative error in the analysis was about 1.0%. When a sample was concentrated, it was diluted to be within the calibration range.

For each type of packing pressure drop measurements were made. This involved varying the water rate and measuring water rate, water temperature, and pressure drop. In the course of the investigation, it was found that trial-and-error repacking of the column was required often until a symmetrically packed bed was achieved, as indicated by a symmetrical concentration profile.

The air apparatus was loaded dry; the packing was dumped in from a bucket. After the air rate was set, the carbon dioxide was adjusted until the ratio of the carbon dioxide flow to the air flow was  $0.0156 \pm 0.002$ . The apparatus was brought to steady-state conditions for one-half hour and sampling was begun. Sampling velocity again was adjusted until it was approximately equal to the main stream velocity. The vacuum required to suck the sample through the rotameters and the thermal conductivity meter was supplied by a water aspirator.

The thermal conductivity meter used was a Leeds and Northrup two-cell type, with off-stream cells which are flushed by thermal syphon effect. The meter was immersed in a constant temperature bath controlled to  $\pm 0.03^\circ\text{C}$ , and the current through the meter was maintained constant to 1 part in 3000. The unbalance voltage across the meter bridge was measured with a Leeds and Northrup precision portable potentiometer. Since water vapor affects the readings of the meter, both cells of the meter were fitted with sulfuric acid bubbler-type dryers having fritted gas dispersers. The traverse sample was drawn through one side of the meter and a trickle of pure air through the other side, which served as a standard. A cell current of 500 mA, was first used, but was found to cause serious instability in the meter readings, and was therefore reduced to 300 mA, which produced a satisfactory stabilization of the meter. In calibrating the instrument, mixtures of known concentration were made up by mixing streams of air and carbon dioxide in known proportions. A log-log plot of the difference between the unbalance e.m.f. and the zero point, e.m.f., vs. volume %  $\text{CO}_2$  in bone dry air yielded a good straight line. The meter was sufficiently sensitive to detect a difference of 0.002%  $\text{CO}_2$  over a wide range of concentrations.

#### Treatment of Data.

**Choice of Equations.** Equations (8) and (13) are alternate solutions and it is important to know under which conditions the more complex or the simpler form may be used. Figure 5 provides a graphical comparison of the two equations. Calculated profiles are shown for various values of  $a$ , with  $z = 30.6 \text{ cm}$ , and  $a = 2.63 \text{ cm}$ . The solid lines were computed from Equation (8) and the dotted from (13). Note that the profiles calculated from the two expressions diverge increasingly as the value of  $a$  decreases, so that for small values of  $a$ , Equation (13) must be employed to represent the profile accurately. As another criterion one may stipulate that

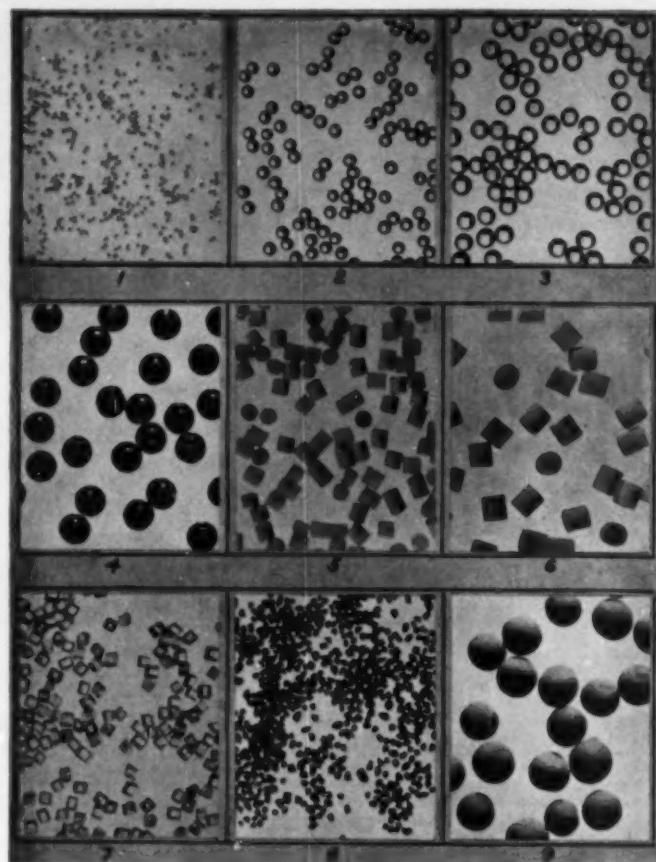


Fig. 4. Photographs of Particles Used in Packed Beds.

for profiles in which the ratio of the maximum concentration to the concentration at the wall is less than 6:1, Equation (13) should be used. This ratio can be increased by decreasing  $a$ , but for the larger packing sizes, short beds do not represent a uniformly packed condition correctly, so that  $a$  cannot always be reduced enough to make the simpler Equation (8) valid.

**Illustration of Application of Equation (8).** In applying Equation (8) to the results of a run, it is first written in the form  $\ln C/C_a = s + tr^2$ , where  $s = a^2/4z$  and  $t = -a/4z$ . This is a linear equation in  $\ln C/C_a$  and  $r^2$ , and the method of least squares may be used in applying it to experimental data. Unfortunately, this method is correct only when the absolute error in the dependent variable is constant. However, in view of the various experimental uncertainties, it is more logical to assume this latter condition, rather than attempt to estimate the nature of the variation in the error, and to weight the squared residuals accordingly. With the above assumption, application of least squares yields

$$t = \frac{\sum r^2 \ln C/C_a - n \sum r^2 \ln C/C_a}{(\sum r^2)^2 - n \sum r^2} \quad (15)$$

where  $n$  is the number of units treated in the summation.

Figure 6 is a plot of the concentration profile of Run 13 (water apparatus) to which Equation (15) may be applied. The plot is folded and the two sides of the profile matched in order to determine the center of symmetry,  $c'$ , of the profile, which may be slightly displaced from the axis of the column. Figure 7 is a plot of Run 13 according to the linear form of Equation (8). Note that the point nearest the wall of the tube is above the plotted line, as expected. Therefore, only 11 of the 12 experimental values can be used in the least squares summation. At the lowest flow rates and with larger packing sizes, the profiles are more irregular than Figure 6 would indicate, but the least-squares method yields a value of  $a$ , no matter how irregular the profile may be. Sample Data Sheet I illustrates the application of Equation (15) to Run 13.

**Illustration of Application of Equation (13).** In cases where Equation (13) must be used, the problem of working with an infinite series of terms arises. Fortunately, in such cases, the series converges fast

TABLE 2.—EDDY DIFFUSION TABLE

(Liquid Phase Experiments unless otherwise noted)

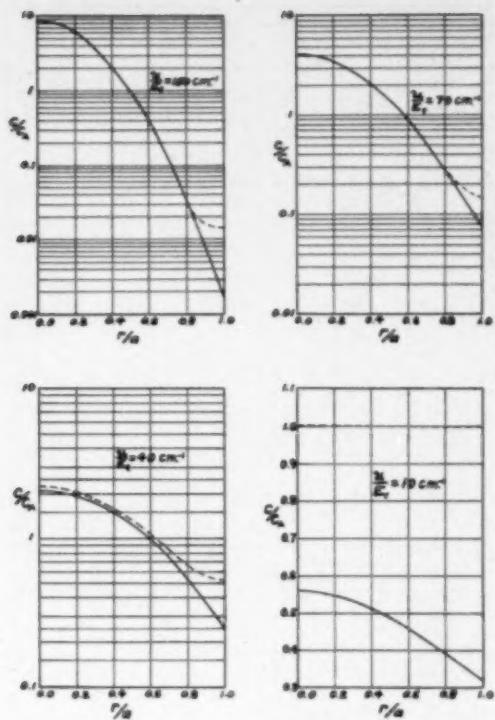


Fig. 5. Concentration Profiles Computed from Equations 8 and 13 for Various Values of  $s$  ( $\sigma/\epsilon = 11.6$ ). Illus. illustrates Limits of Applicability of Each.

## SAMPLE DATA SHEET I

Run 13 (Water Experiment) 1 mm. glass spheres pitot traverse center = 6.38 cm. z = 30.60 cm.

No.	Traverse Position cm.	Sample C	Mixture C <sub>A</sub>	C/C <sub>A</sub>
1	3.80	0.011	0.789	0.014
2	4.25	0.033	0.789	0.043
3	4.70	0.083	0.789	0.104
4	5.15	0.209	0.838	0.248
5	5.60	0.355	0.835	0.420
6	6.00	0.47	0.833	0.57
7	6.50	0.60	0.831	0.730
8	6.90	0.49	0.842	0.58
9	7.35	0.205	0.840	0.246
10	7.80	0.587	0.839	0.676
11	8.20	0.185	0.864	0.179
12	8.60	0.023	0.840	0.027

Av.

No.	r in cm. $c' = 6.36$	$r^2$	$r^4$	$\ln C/C_A$	$r \ln C/C_A$
1	2.56	6.56	19.8	-1.170	-14.13
2	2.11	4.46	12.57	-1.074	-12.36
3	1.65	2.25	5.57	-1.074	-10.47
4	1.21	1.46	2.13	-0.924	-8.36
5	0.76	0.58	0.33	-1.459	-0.94
6	0.36	0.13	0.02	-1.981	-0.24
7	0.14	0.02	0.00	-1.968	-0.04
8	0.54	0.29	0.09	-1.673	-0.49
9	0.99	0.98	0.96	-0.909	-0.93
10	1.44	2.08	4.73	-0.722	-5.82
11	1.84	3.28	11.48	-1.730	-5.82
12	2.34	5.01	25.10	-2.615	-18.10
2	....	21.14	71.87	-1.746	-38.87

Temp. = 63.3° F.

$$t = \frac{21.14(-1.746) - 11(-38.87)}{(21.14)^2 - 11(71.87)} = -1.137 = a/4\pi$$

$$a = -4(30.60)(-1.137) = 139.1 \text{ cm.}^2$$

Water Rate = 0.465 lb./sec. Water Viscosity = 1.077 cP.

$$Re' = D_p G_a / \mu = \frac{0.0366}{12} \times \frac{0.465}{(\pi/4)(2.067/12)^2} = 84.3$$

$$Pe' = D_p E / D_{pA} = (0.0366)(2.54)(139.1) = 12.90$$

## 1-mm. spheres

Run No.	Re'	Pe'
5	4.21	16.92
6	10.82	7.50
9	31.38	19.56
10	9.95	13.70
11	26.5	12.37
12	53.8	11.93
13	84.3	12.98
14	138.0	11.78
15	167.6	11.93
27	7.00	6.00

## 2-mm. spheres

Run No.	Re'	Pe'
42	965	11.98
43	662	11.77
44	425	11.90
45	257	11.80
46	164.0	12.37
47	89.3	13.00
48	47.5	11.15

## 3-mm. spheres

Run No.	Re'	Pe'
51	2400	12.55
52	1703	11.95
53	1064	10.88
54	616	10.52
55	376	10.10
56	211	7.83
57	120.2	13.32

## 4-mm. spheres

Run No.	Re'	Pe'
60	1376	11.70
61	865	11.66
62	360	11.50
63	210.5	10.89
64	132.0	10.36
65	71.1	15.03
66	35.6	ca. 30
67	28.5	11.30
68	9.90	14.60

## 3/16 × 3/16-in. cylinders

Run No.	Re'	Pe'
72	1400	10.80
73	1069	10.89
74	675	10.45
75	407	10.45
76	257	8.55
77	130.0	6.95
78	78.5	5.54

## 1/4-in. cylinders

Run No.	Re'	Pe'
79	2030	10.86
80	1460	10.40
81	922	9.44
82	561	6.71
83	328	8.80
84	189.0	8.88

## 1/4-in. cubes

Run No.	Re'	Pe'
85	907	6.63
86	584	8.78
87	368	8.63
88	230.5	8.67
89	156.0	7.78
90	89.9	7.71
91	47.0	7.50
92	23.8	10.80

## 10-14 mesh granules

Run No.	Re'	Pe'
96	310	7.00
97	211.8	7.33
98	138.8	7.98
99	77.7	7.55
100	54.4	8.00
101	33.7	7.78
102	20.30	9.88
103	10.80	18.38

## Mixed 1-mm. and 3-mm. spheres

Run No.	Re'	Pe'
117	526	10.20
118	326	11.71
119	212.0	12.60
120	131.7	10.61
121	76.0	7.76
122	40.8	13.70
123	19.48	15.38

## 3/4-in. spheres (Air Apparatus)

Run No.	Re'	Pe'
125	645	10.08
126	406	10.00
127	274	10.03
128	174.3	10.20
129	110.8	11.00
130	73.4	11.60
131	47.8	12.65
132	28.4	11.48

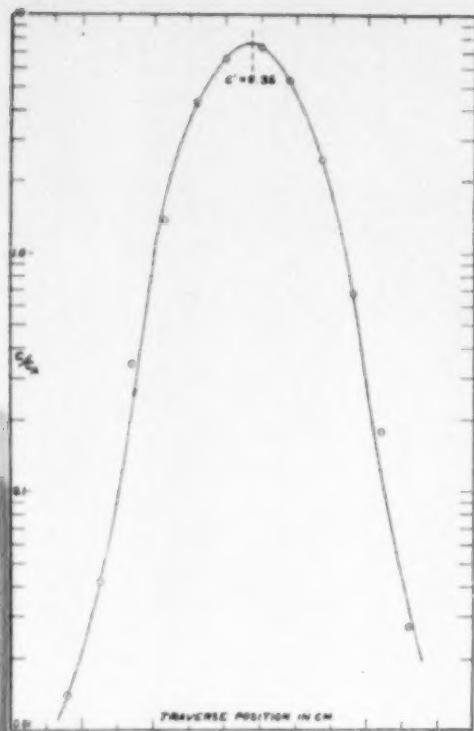


Fig. 6. Concentration Profile for Water Run No. 13.

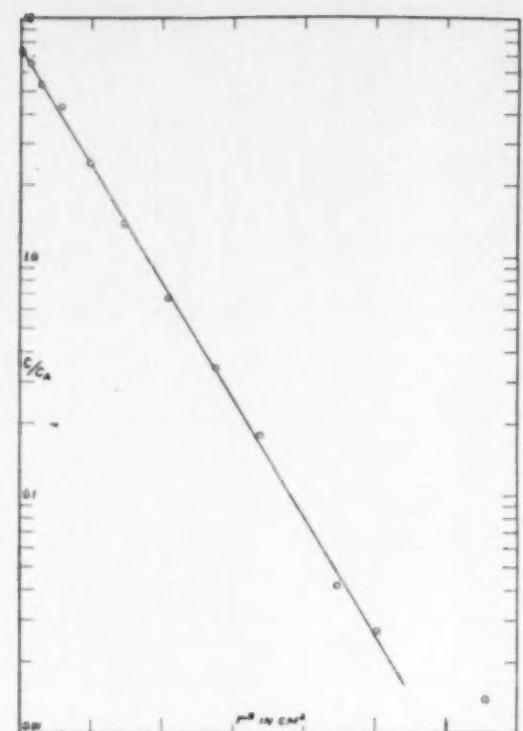


Fig. 7. Plot of  $\log C/C_A$  vs.  $r^2$  for Data of Run No. 13 Demonstrating Application of Equation 8.

ough so that no more than the first two variable terms need be used. Symbolizing the constant coefficients by  $S$  and  $T$ , Equation (13) becomes

$$(C/C_A)(1/B) = 1 + SJ_s(\beta\sigma) + TJ_s(\beta\sigma) \quad (16)$$

Since (16) is linear in form, the theory of least squares can be applied, giving the following expressions for the coefficients

$C/C_A$  vs.  $r^2$ , used in the determination of  $B$ . The two broken lines, which are drawn through the circles and triangles respectively, represent the two sides of the profile. Note that the data are extrapolated to the wall, making use of the fact that the profile must meet the wall at right angles. The solid line, which is drawn half-way between the two broken lines, is representative of the average half-profile, and the area under

$$S = \frac{\sum [J_s(\beta\sigma)]^2 \times [\sum (C/C_A)(1/B)J_s(\beta\sigma) - \sum J_s(\beta\sigma)]}{\sum [J_s(\beta\sigma)]^2 \times \sum [J_s(\beta\sigma)]^2 - [\sum J_s(\beta\sigma)]^2} \quad (17)$$

$$T = \frac{\sum [J_s(\beta\sigma)]^2 \times [\sum (C/C_A)(1/B)J_s(\beta\sigma) - \sum J_s(\beta\sigma)]}{\sum [J_s(\beta\sigma)]^2 \times \sum [J_s(\beta\sigma)]^2 - [\sum J_s(\beta\sigma)]^2} \quad (18)$$

For all cases in which the series expansion must be used,  $T$  is smaller than  $S$  by at least one order of magnitude. For profiles with ratios of  $C_{max}/C_{min}$  less than 3:1,  $T$  is negligible. Sample Data Sheet II illustrates the application of Equations (17) and (18) to Run 72 (water apparatus). In this case, since the effect of the wall is taken into account, it seems more reasonable to use the center of the pitot traverse (the geometric center of the pipe) rather than the apparent center of symmetry of the profile, in calculating  $r$ . Figure 8 is a plot

this solid line, between  $r^2 = 0$  and  $r^2 = 6.90 = a^2$ , equals

$$\int_0^{a^2} (C/C_A)2rdr,$$

so that  $B$  is equal to  $(1/6.90)$  times this area. As shown on Sample Data Sheet II, the value of  $a$  obtained from  $T$  is somewhat different from that obtained from  $S$ . Since  $T$  is much smaller than  $S$ , any error inherent in the experiment will have a much greater relative effect upon the former than on the latter. Thus the value of  $a$  obtained

from  $T$  cannot be relied upon, and has not been used in calculating the final results of this investigation.

*Definition of Pe'. As discussed previously, values of the ratio  $w/E$  for turbulence alone may be computed from a with due regard for molecular diffusion and fraction void. In order to relate  $w/E$  with the system parameters it is appropriate to use a dimensionless group. Since  $w/E$  has the dimension  $L^4$ , multiplication by a geometric scale factor will produce a dimensionless group. Since the turbulence is particle-generated, particle diameter,  $D_p$  is an appropriate choice. The resulting group,  $D_p w/E$  is similar to the Pelet group used in heat-transfer work and is named a modified Pelet group, symbolized by  $Pe'$ .*

## Results

A plot of a modified Pelet group,  $Pe'$ , previously defined, vs. a modified Reynolds number,  $Re' = D_p V_o / \mu_s$ , with  $D_p/D_t$  as an independent parameter fulfills the requirements of dimensional analysis and the data are presented in this form. Table 2 contains all eddy diffusion data.

Figure 9 is a plot of  $Pe'$  vs.  $\log Re'$  for the four sizes of spherical packing used in the water apparatus. Note that two regions are indicated for each size of packing. The region represented by

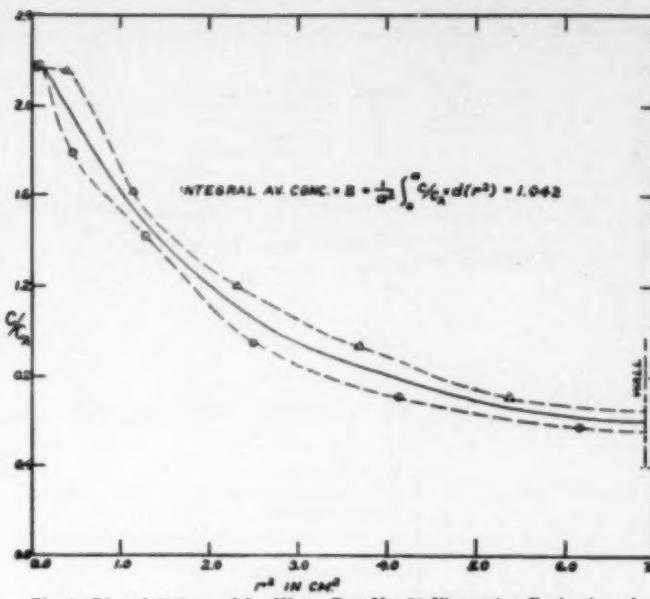


Fig. 8. Plot of  $C/C_0$  vs.  $r^2$  for Water Run No. 72 Illustrating Evaluation of Constant,  $B$  in Equation 13.

the heavy, solid lines is characterized experimentally by regular concentration profiles, the analysis of which leads to reliable values of  $a$ . The region represented by the lighter, broken lines is characterized experimentally by irregular concentration profiles, leading to uncertainty in the values of  $a$  obtained from them. Experiments with a glass-observing section in place of the sampling section of the water apparatus have shown that large eddies, with dia-

meters several times that of the packing, exist within the bed in this latter region. The linear  $Pe'$  scale, used to emphasize the slopes of the solid lines, also emphasizes the deviations of the experimental points from the plotted lines, the maximum deviation actually being only about 5%. The slope of the solid line is slightly negative for the smallest packing and increases toward zero to small positive values as  $D_p/D_t$  is increased. Since the value of  $D_p/D_t$  is small for

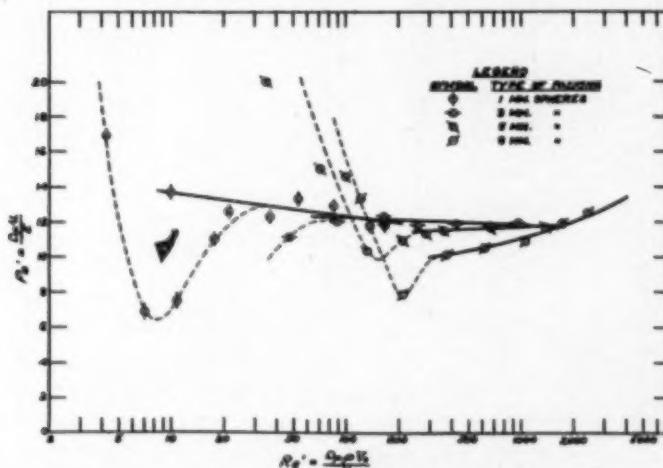


Fig. 9. Diffusivity Results.  
Plot of  $Pe'$  vs.  $\log Re'$  for Beds of Uniformly Sized Spherical Particles in Water Apparatus.

the 1-mm. packing, it is reasonable to assume that the solid line drawn for this size of packing is close to the limiting line for  $D_p/D_t = 0$ . It may be noted also that the break between the two regions moves forward with increasing  $D_p/D_t$ , and that the advance in position occurs roughly in direct proportion to  $D_p/D_t$ . It may be noted that because  $Pe'$  varies only slightly with  $Re'$ , the turbulent eddy coefficient,  $E$ , varies almost directly with fluid velocity and can quickly outstrip molecular diffusion in importance.

Figure 10 is a plot of  $Pe'$  vs.  $\log Re'$  for the four types of nonspherical packing used in the water apparatus. There does not seem to be any regularity in the shape of the curves in the broken line region, but the solid lines all have small slopes, as with spheres, and these slopes are about the same function of  $D_p/D_t$  as in the case of spherical packing. Also, the lines for the nonspherical packing are seen to be displaced vertically downward toward lower values of  $Pe'$ , when compared with the results for spherical packing, and the displacement increases as the particle shape deviates more and more widely from the spherical.

In correlating the solid-line or stable regime data for various packings an exponential equation was used of the form  $Pe' = m(Re')^n$  in which  $n$  is a function of  $D_p/D_t$  and  $m$  is a function of both  $D_p/D_t$  and  $\lambda$ , a shape factor. The resulting equation is:

$$Pe' = \frac{(1.15/\lambda) - 0.15}{17.4(D_p/D_t)^{0.70} + 0.0650} \times (Re')^{[4.20(D_p/D_t)^{1.00} - 0.050]} \quad (19)$$

$\lambda$  is the shape factor as defined by Leva (7),  $\lambda = 0.205 a/V\%$  ( $a$  is the surface area per unit volume and  $V$  is its volume).

This expression fits the stable region data for spheres to within 5%, and for nonspherical particles to within 10%. It should not be used for values of  $D_p/D_t$  greater than 0.17 with spheres, or greater than 0.11 with nonspherical particles, but it probably can be employed to extrapolate the experimental results to  $Re' = 5000$ , without entailing an error of more than 15%. It is not valid, of course, in the broken line or unstable region. For spheres, in view of the rough proportionality between the position of the break between the two regions and  $D_p/D_t$ , the lower limit of the stable region can be expressed in the form  $Re' = 2150(D_p/D_t)$ . This limiting equation is not very accurate because of the uncertainty connected with measurements in the unstable region, but it can serve as a useful approximate limit to the validity of the general equation

in the case of spheres. In the absence of more satisfactory unstable region data for nonspherical particles, the limiting equation will be assumed to apply for these shapes as well.

Figure 11 shows results obtained with mixed packing in the water apparatus, and with  $\frac{3}{16}$ -in. spheres in the air apparatus. The former packing is a mixture of 1-mm. and 3-mm. spheres, containing 62.4% by volume of the larger spheres. This particular concentration gives a minimum fraction void according to Furnas (5). The actual measured value of  $\epsilon$  was 0.297. An average  $D_p$ , weighted by volume fraction of the individual components, has been used in the plot, and the plot for 1-mm. spheres has been included for purposes of comparison. Note that the stable region line occurs in the correct position.

The stable region line for the  $\frac{3}{16}$ -in. spheres in the air apparatus is seen to be displaced downward from the expected position by about 15%. However, this difference is surprisingly small in view of the enormous difference in the characteristics of the two main stream fluids, and is a good deal smaller than the errors which are encountered often in correlations of heat transfer or diffusion measurements on widely divergent systems. The broken line region does not have the same shape as the unstable regions encountered with spherical packing in the water apparatus. It has been indicated by a broken line because it seems distinct from the normal stable region encountered at higher values of  $Re'$ .

An important experimental finding which also was an underlying assumption in this work deserves emphasis. It is that the value of  $a$  (or  $E_t$  at constant  $u$ ) is constant and independent of radial position. As an example, statistical analysis of a typical run having 12 traverse readings results in a single value of  $a/E_t$  at any radial position within a precision of 6.3% at a confidence level of 95%.

Figures 12-14 present results of pressure-drop measurements on the various packings. They are standard plots of the log of the modified friction factor  $f'$  vs.  $\log Re'$ ,  $f'$  being defined as  $g_p D_p \Delta P / 2 L G_o^2$ . Figure 12, for the spheres, shows no anomalous features that need explanation. In Figure 13, for the nonspherical packing, it is noted that the curve for the  $\frac{3}{16}$ -in.  $\times \frac{3}{16}$ -in. cylinders rises in an abnormal manner at lower values of  $Re'$ . These particles were difficult to wet with water and tended to hold air within the bed. The  $f' - Re'$  curve for 3-mm. spheres has been plotted on Figure 14 for comparison purposes. To this end, the values of  $f'$  for the mixed packing have been corrected to = 0.386 (the value for the

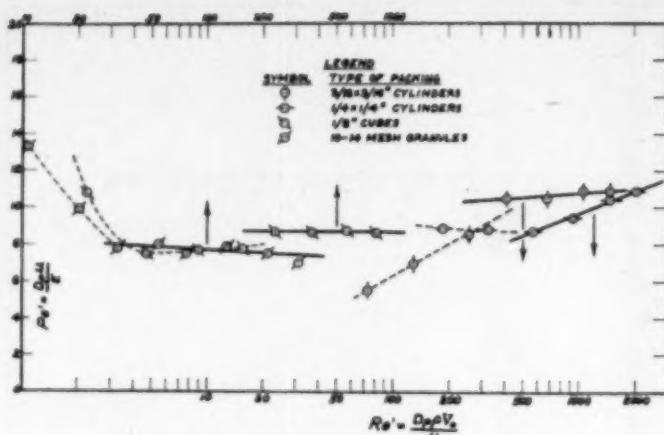


Fig. 10. Diffusivity Results.  
Plot of  $P_c$  vs.  $\log Re'$  for Beds of Uniformly Sized Nonspherical Particles in Water Apparatus.

#### SAMPLE DATA SHEET II

##### Run 72 (Water Experiment) 3/16-in. aluminum cylinders

$a = 16.12$  cm.      Pitot traverse center = 6.28 cm.

No.	Traverse Position cm.	Sample C	Mixture C <sub>A</sub>	C/C <sub>A</sub>
1	3.89	0.190	0.239	0.828
2	4.25	0.207	0.246	0.705
3	4.70	0.223	0.241	0.948
4	5.15	0.477	0.336	1.420
5	5.60	0.403	0.336	1.791
6	6.00	0.737	0.336	2.180
7	6.50	0.732	0.338	2.163
8	6.99	0.730	0.338	2.158
9	7.35	0.544	0.336	1.618
10	7.80	0.404	0.338	1.200
11	8.20	0.813	0.336	0.929
12	8.60	0.337	0.336	0.705
$\Sigma$		8.371	1.596	8.030
				3.967
				3.907

No.	$[J_e(\beta_1 r)]^2$	$J_e(\beta_1 r) \times$	$J_e(\beta_1 r) \times$	
1	0.076	-0.108	$B = 1.042$	
2	0.061	+0.009		
3	0.139	-0.019	$2.390 [8.030 (1/1.042) - 3.371]$	
4	0.069	-0.111	$B = -1.886 [3.967 (1/1.042) - 1.596]$	
5	0.107	+0.251	$2.390 \times 3.907 - (1.886)^2$	
6	0.740	+0.825		
7	0.826	+0.887	$B = 1.067$	
8	0.177	+0.186		
9	0.042	-0.098	$3.907 [3.967 (1/1.042) - 1.596]$	
10	0.153	-0.040	$B = -1.886 [8.030 (1/1.042) - 3.371]$	
11	0.017	+0.025	$2.390 \times 3.907 - (1.886)^2$	
12	0.041	-0.073		
$\Sigma$	2.390	1.886	$T = 0.0813$	

$$1.067 = \frac{a}{[J_e(\beta_1 r)]^2 a^2 + 4\beta_1^2]^{1/2}} e^{-[a - (a^2 + 4\beta_1^2)^{1/2}]r/2}$$

$a$  is the only unknown in the above equation. If an approximate value of  $a$ , estimated from the ratio  $C_{max}/C_{min}$  of the profile, is substituted into the fraction

$$a/(a^2 + 4\beta_1^2)^{1/2}$$

so that an approximate value of this fraction is determined,  $a$  is then only contained in the exponential, and the simplified equation can be solved directly, giving a good approximate value of  $a$ . If this value is placed back into the fraction, the next approximation of  $a$  will be more than sufficiently accurate. The same method is used in obtaining a value of  $a$  from  $T$ . These values compare as follows:  $a = 19.60$  cm.,  $a_p = 25.2$  cm.

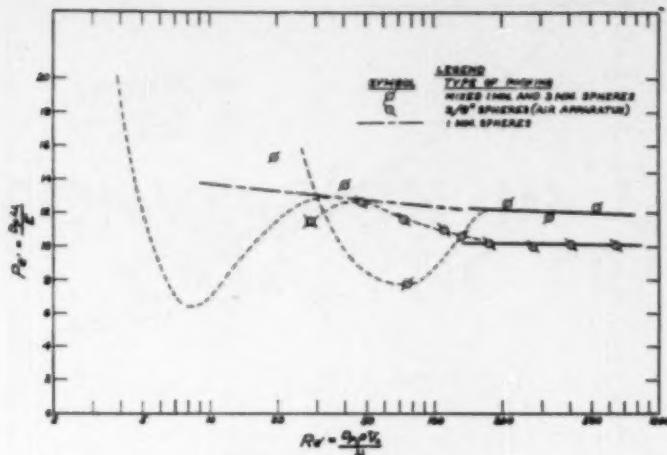


Fig. 11. Diffusivity Results.

Plot of  $P'e'$  vs.  $\log Re'$  for a Bed of  $\frac{1}{2}$ -in. Spheres in Air Apparatus. Also, for bed of mixed 1-mm. and 3-mm. spheres in water apparatus.

3-mm. spheres) by means of the correction factor contained in Leva's work (7).  $D_p$  is again the average diameter, weighted by volume fraction. The curve for the mixed packing is seen to be displaced upward by a factor of 2.7, so that the use of this average  $D_p$  does not give a satisfactory correlation.

#### Comment

The  $f' - Re'$  curves give information about flow conditions within a packed

bed. Their slopes change gradually from the  $-1$  in the viscous region to about  $-0.2$  at high values of  $Re'$ , in contrast to the  $f - Re$  curve for an empty pipe, which shows a sharp break across the transition region between viscous and turbulent flow. This difference indicates that there is no sudden onset of turbulence beyond a certain value of  $Re'$  in a packed bed, but that whatever type of turbulence actually exists in the bed develops gradually over a consider-

able range of flows. Also, pressure-drop measurements are correlated satisfactorily by the use of  $D_p$ ,  $D_t$  having only a minor effect, so that the turbulence in packed beds most likely is connected with the packing size and must therefore be interstitial in character. The stable, solid-line region on the  $P'e' - Re'$  plots also is considered to be representative of interstitial turbulence, since the correlation by the use of  $D_p$  in  $P'e'$  in this region is satisfactory.

In view of the fact that the unstable region of the curves on Figure 12 moves forward in proportion to  $D_p/D_t$ , it is obvious that had the Reynolds number been based on  $D_t$  instead of  $D_p$ , these curves would have been pulled together. This indicates that the large eddies are a function of  $D_t$  rather than  $D_p$ , i.e., are controlled by the wall of the containing tube, rather than by the packing itself.

In a highly simplified approach to the stable turbulence pattern it may be assumed that for any particular shape of packing, geometric similarity always is maintained, regardless of the value of  $Re'$ . This means that the scale of turbulence is always proportional to the particle size, and that the root mean-square deviating velocity is proportional always to the velocity within the bed. Stated mathematically, the scale  $d = K_1 D_p$  and the root mean-square deviating velocity  $v' = K_2 u$ . For geometrically similar systems,  $E$  is proportional to  $dv'$  so that  $E = K_3 D_p u$ , and  $P'e' = D_p u/E = 1/K_3 = K_4$ . This prediction of the constancy of  $P'e'$  fits well the results in the turbulent region, since in all cases the slope of the turbulent region line is not great.

With regard to the relationship between  $P'e'$  and the shape of the packing particles, it is reasonable to assume that the presence of sharp edges at the particle surface should increase the intensity of turbulence, thereby increasing  $E$  and depressing  $P'e'$  relative to the value for spheres. It is interesting to note that even in the case of the sharp-edged granules,  $P'e'$  is depressed by only 35%.

#### Acknowledgment

This work was performed on part of a project and fellowship for the study of heat transfer and kinetics in flow systems sponsored by the Shell Oil Co., Inc. The support, interest and cooperation of this company are gratefully acknowledged.

#### Notation

##### Dimensional Legend

- $L$  = Length
- $M$  = Mass
- $H$  = Quantity of Heat
- $\theta$  = Time
- $d$  = Temperature

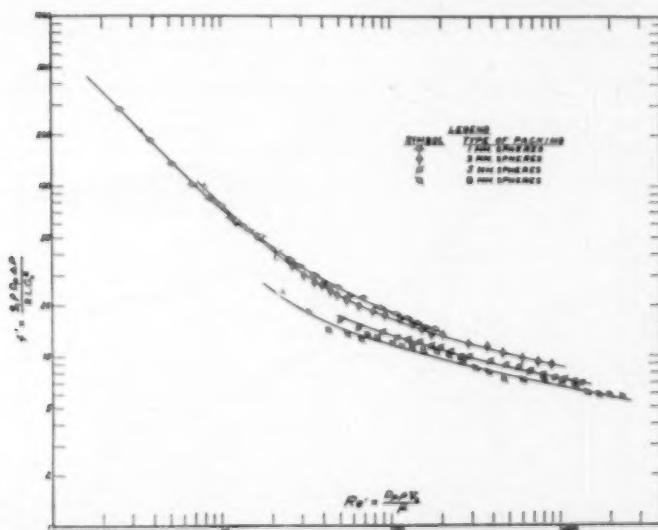


Fig. 12. Plot of  $\log f'$  vs.  $Re'$  for Beds of Uniformly Sized Spherical Particles in Water Apparatus.

- $a$  = radius or half-width of pipe or conduit, ( $L$ )  
 $B$  = a constant  
 $c$  = specific heat of fluid, ( $H/Md$ )  
 $c'$  = center of symmetry of profile  
 $C$  = concentration of diffusing material, ( $M/L^3$ )  
 $C_A$  = mixed average effluent concentration of diffusing material, ( $M/L^3$ )  
 $D$  = molecular diffusivity, ( $L^2/\theta$ )  
 $D_p$  = particle diameter in packed bed ( $L$ )  
 $D_t$  = diameter of containing tube ( $L$ )  
 $d$  = scale of turbulence in packed bed ( $L$ )  
 $E$  = eddy diffusivity, ( $L^2/\theta$ )  
 $E_t$  = total diffusivity,  $E + D$ , ( $L^2/\theta$ )  
 $f$  = friction factor in empty tube, (dimensionless)  
 $f'$  = friction factor in packed bed, (dimensionless)  
 $G_e$  = mass rate of flow, based on empty tube, ( $M/L^2\theta$ )  
 $g_e$  = gravitational constant, ( $L^2/\theta$ )  
 $J_0(\cdot)$  = Bessel function of first kind of zero order, (dimensionless)  
 $J_1(\cdot)$  = Bessel function of first kind of 1st order (dimensionless)  
 $k$  = molecular thermal conductivity of fluid, ( $H/L\theta d$ )  
 $L$  = length of packed bed, ( $L$ )  
 $N$  = rate of mass transfer,  $M/\theta L^2$   
 $\Delta P$  = pressure drop across bed, ( $M/L\theta^2$ )  
 $Pc'$  = modified Pecllet number =  $D_p u/E$ , (dimensionless)  
 $Q$  = rate of injection of diffusing substance, ( $M/\theta$ )  
 $q$  = amount of tracer material when placed instantaneously, ( $M$ )  
 $q'$  = rate of heat transfer, ( $H/\theta L^2$ )  
 $r$  = radial coordinate in cylindrical coordinates, ( $L$ )  
 $Re'$  = Reynolds number for packed bed, based on  $D_p$ , (dimensionless)  
 $t$  = time, ( $\theta$ )  
 $u$  = mean, point-condition velocity in  $z$  direction in cylindrical coordinates, ( $L/\theta$ )  
 $V_a$  = integral average velocity, based on empty tube, ( $L/\theta$ )  
 $v'$  = root mean-square value of deviating velocity, ( $L/\theta$ )  
 $z$  = longitudinal coordinate in cylindrical coordinates, ( $L$ )  
 $a = u/E_t, (1/L)$   
 $a' = V_a/E_t(1/L)$   
 $\beta$  = positive root of Bessel function of first order, first kind

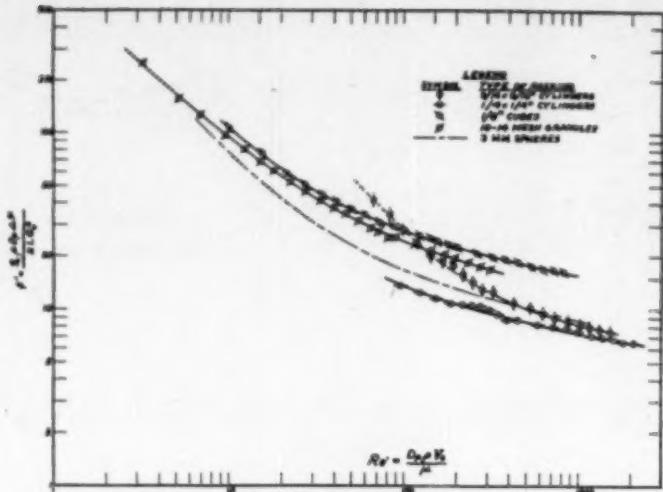


Fig. 13. Plot of  $f'$  vs.  $\log Re'$  for Beds of Uniformly Sized Nonspherical Particles in Water Apparatus.

- $\lambda$  = shape factor of particle, (dimensionless, see text)  
 $\epsilon$  = fraction voids in bed, (dimensionless)  
 $\rho$  = fluid density, ( $M/L^3$ )  
 $\mu$  = molecular viscosity of fluid, ( $M/L\theta$ )

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(Presented at Forty-first Annual Meeting, New York, N. Y.)

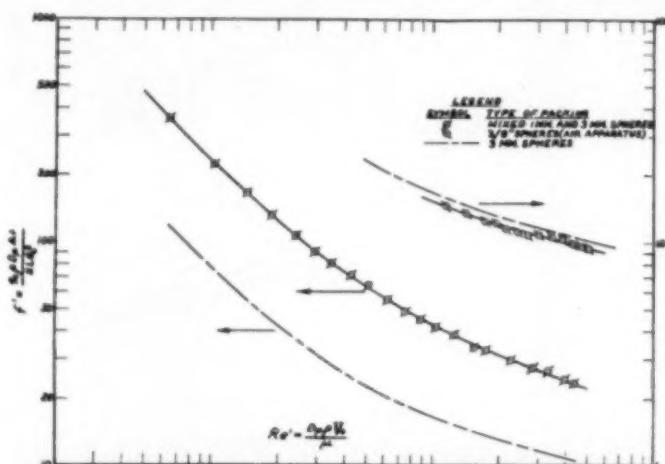


Fig. 14. Plot of  $\log f'$  vs.  $Re'$  for a Bed of  $5/16$ -in. Spheres in Air Apparatus. Also, for bed of mixed 1-mm. and 3-mm. spheres in water apparatus.

# CONVERSION IN THERMOFOR CATALYTIC CRACKING

R. A. McKEAN and L. F. GRANDEY

Union Oil Company of California, Wilmington, California

In the past few years catalytic cracking has assumed an increasingly important role in petroleum refining. A constant problem to the refiner is how to secure the maximum yield of cracked products.

This paper presents an improved correlation of feed-stock conversion with space velocity and catalyst-to-oil ratio. This correlation is based on an empirical formula tested with pilot plant and commercial data.

THE operator of a petroleum catalytic cracking facility desires to derive the maximum profit from his cracking plant. Usually this is interpreted to mean maximum possible gasoline production. For this reason the petroleum process engineer is frequently asked, "How can we, by changing process conditions, increase gasoline production?" This paper is an attempt to present partial answers to this question.

In Thermofor Catalytic Cracking the common process variables are (1) oil-residence time, (2) catalyst-to-oil ratio, (3) reaction temperature, (4) catalyst activity and (5) feed-stock characteristics. Because the effect, in both direction and degree, of a change in one of the catalytic cracking process variables is dependent on the location of the over-cracking region, it is convenient to study the effect of the process variables in two stages. The first stage is the study of the effect of the process variables on gas oil conversion. Conversion ( $C$ ) is defined as the volume fraction or volume per cent of the original gas oil charge that is converted to gas, gasoline and coke. This quantity is calculated by difference according to the formula,  $C = 1.00 - P$ , where  $P$  is the volume fraction of gas oil range material appearing in the product. It has been found that an increase in one of the process variables always results in an increased conversion.

The second step in the problem is determining how the gas, gasoline and

coke are distributed at a given conversion and for a given set of process variables. In other words, given a conversion derived in first step, how much gasoline will result? This problem has been discussed elsewhere and is not considered in this paper.

A survey of the pilot plant data available on Thermofor Catalytic Cracking (TCC) has been made with the object of correlating the data to determine

more precisely the effect of the chief operating variables. The result of this survey was the development of a correlation for oil-residence time and catalyst-to-oil ratio.

*Oil-Residence Time Related to Conversion.* Thermofor Catalytic Cracking data on the effect of oil-residence time and catalyst-to-oil ratio have been correlated by several methods. Predominantly, the correlations are based on a mathematical expression of the form

$$Y = KX^n \quad (1)$$

or expressed in another form,

$$\ln Y' = \ln X + \ln K \quad (1a)$$

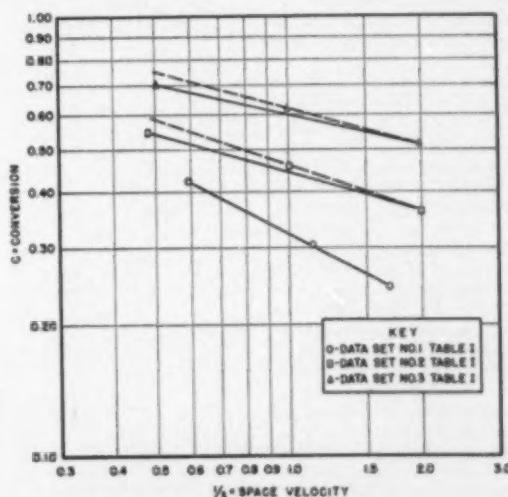


Fig. 1. Conversion vs. Space Velocity.

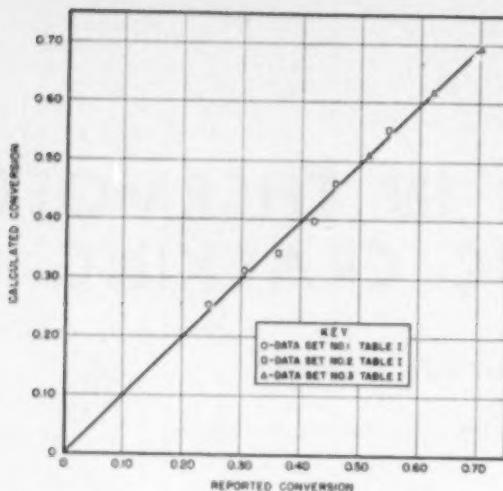


Fig. 2. Calculated Conversion vs. Reported Conversion.

where:

$Y$  = conversion; volume fraction

$X$  = oil-residence time, or catalyst-to-oil ratio

$K$  = a constant determined by all TCC variables other than the one being varied (either oil-residence time or catalyst-to-oil ratio)

$n$  = constant

This expression graphs as a straight line on a log-log coordinate system. The plot of either oil-residence-time data or catalyst-to-oil-ratio data on log-log coordinates does approximate a straight line when the data span only a small range of conversion. This has undoubtedly led to the adoption of the above expression as a correlating function. Figure 1 is a plot on log-log coordinates of data used in this report and is typical of all the data reviewed. The chief weakness of this plot is that it fails to define the terminal conditions. Extrapolation of the straight lines could result in conversions above 1.00. Also, as seen from Figure 1, extrapolation of experimental data can result in significant errors. It is this fact which indicated the need for an improved correlating expression.

The oil-residence time and catalyst-to-oil-ratio data reviewed in this correlation study were predominantly developed in pilot plant studies (Tables 1 and 2). Pilot plants from which the data were derived were all of the continuous type. A stream of oil vapor was passed through a moving bed of catalyst. Data

were obtained for both countercurrent and concurrent flow of oil and catalyst. The data span a conversion range of 25 to 85%. All these data were first plotted on a log-log system of coordinates to check the validity of the correlating formula (see 1a). It was found that the value of the coefficient  $n$  progressively decreased as the conversion level increased. This can be seen from the slopes of the lines on Figure 1. This

tendency suggested that an equation of the type

$$Y = KX^{f(Y)} \quad (2)$$

might better satisfy the data. Efforts were directed toward determining the most suitable form of the exponent  $f(Y)$ . The function  $f(Y)$  found best to correlate the data was  $(1 - \sqrt{Y})$ . This function has the desired property of a progressively decreasing value as the value of  $Y$  increases. Thus, the equation adopted for this correlation study is:

$$\ln Y = (1 - \sqrt{Y}) \ln X + \ln K \quad (3)$$

or expressing it in another form:

$$Y = KX^{(1-\sqrt{Y})} \quad (3a)$$

As applied to TCC data on the effect of oil-residence time, Equation (3a) is expressed as:

$$C = K_t t^{(1-\sqrt{C})} \quad (4)$$

where:

$C$  = conversion; volume fraction

$t$  = oil-residence time; hr.

$K_t$  = constant for a given feed stock, catalyst-to-oil ratio, reaction temperature and catalyst activity

NOTE:  $K_t$  may be defined as the crackability of the feed stock at an oil-residence time of 1 hr. and the

TABLE 1.—PILOT PLANT DATA  
TCC Correlation Data      Effect of Oil Residence Time

Data Set No.	Reported		Oil-Residence Time; hr.	$K_t$ (Calc.)
	Conversion Vol. Fraction	Space Velocity		
1	0.421	0.59	1.69	0.350
	0.508	1.13	0.895	0.320
	0.244	1.69	0.591	0.318
Ave. = 0.33				
2	0.543	0.48	2.08	0.450
	0.484	1.00	1.00	0.454
	0.360	2.00	0.50	0.475
Ave. = 0.46				
3	0.700	0.50	2.00	0.62
	0.616	0.99	1.00	0.618
	0.511	1.98	0.503	0.621
Ave. = 0.62				
4	0.627	0.53	1.89	0.548
	0.502	0.98	1.02	0.502
	0.443	1.98	0.505	0.570
Ave. = 0.540				
5	0.67	0.60	1.66	0.611
	0.528	1.80	0.556	0.618
Ave. = 0.615				
6	0.782	0.60	1.66	0.661
	0.631	1.80	0.556	0.710
Ave. = 0.695				
7	0.608	1.01	0.99	0.609
	0.614	1.05	0.954	0.620
	0.524	1.80	0.555	0.618
Ave. = 0.616				

given conditions of the other TCC process variables.

A valuable property of this equation is that it satisfies both terminal conditions besides showing close agreement with experimental data in the middle range. At zero time the equation yields zero conversion and as residence time is allowed to increase without limit, conversion approaches 1.00 as a limiting value.

Table 1 summarizes the data on oil-residence time that were used in this correlation study. Each set of data was obtained on a given feed stock and all variables, other than oil-residence time, were maintained constant. For the reported conversions and oil-residence time of each set of data, a  $K_t$  was calculated. The close agreement of the  $K_t$ 's for any one set of data indicates the above equation correlates the data well. Four sets of the data in Table 1 have been plotted on Figure 3 to show graphically the agreement between the data and the correlating equation. The  $K_t$ 's calculated for any one set of data were averaged to determine the best  $K_t$  for that feed stock, catalyst-to-oil ratio, reaction temperature, and catalyst activity. Then the average  $K_t$  line was drawn for that set of data. Another test of the correlating equation is presented in Figure 2 where the values of  $C$  as

TABLE 2.—PILOT PLANT DATA

TCC Correlation Data

Effect of Catalyst to Oil Ratio

Data Set No.	Conversion Vol. Fraction	Catalyst to Oil Ratio	$K_t$ (Calc.)
1	0.36	1.50	0.306
	0.442	3.01	0.306
	0.511	6.00	0.307
$\bar{K}_t = 0.306$			
2	0.543	1.61	0.482
	0.627	2.90	0.503
	0.706	6.01	0.524
$\bar{K}_t = 0.503$			
3	0.454	1.53	0.395
	0.502	3.03	0.365
	0.618	6.10	0.421
$\bar{K}_t = 0.394$			
4	0.493	1.6	0.414
	0.514	2.4	0.402
	0.565	3.5	0.414
$\bar{K}_t = 0.410$			
5*	0.498	2.06	0.403
	0.534	2.56	0.426
	0.532	2.53	0.416
	0.557	2.64	0.427
	0.581	2.99	0.448
	0.577	3.23	0.425
	0.614	3.44	0.469
$\bar{K}_t = 0.433$			

\* Data on effect of catalyst-to-oil ratio was developed by maintaining constant oil-vapor inlet and catalyst-inlet temperatures, which resulted in an increasing reaction temperature as the catalyst-to-oil ratio increased. Correcting the data to a constant reaction temperature would result in better agreement with the correlating equation. The calculated  $K_t$  would not appear to increase as indicated above.

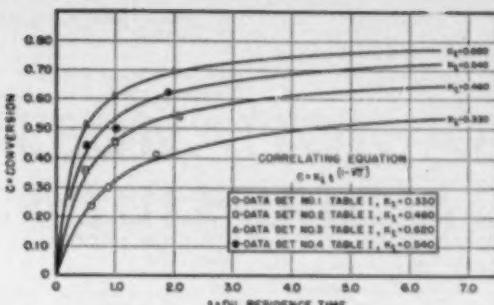


Fig. 3. Conversion vs. Oil-Residence Time.

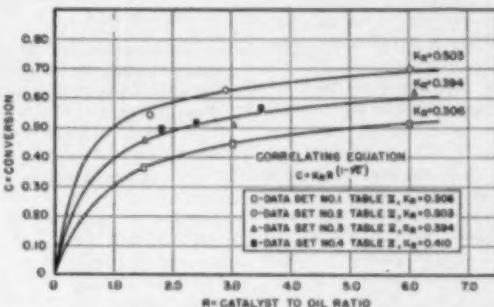


Fig. 4. Conversion vs. Catalyst-to-Oil Ratio.

calculated from the correlating expression are plotted against the experimental values of  $C$ . Proximity of the points to the 45° line is evidence of the close agreement of the two values.

*Catalyst-to-Oil Ratio Related to Conversion.* For the correlation of TCC data on the effect of catalyst-to-oil ratio, Equation (3a) is expressed as:

$$C = K_R R^{(1-\sqrt{C})} \quad (5)$$

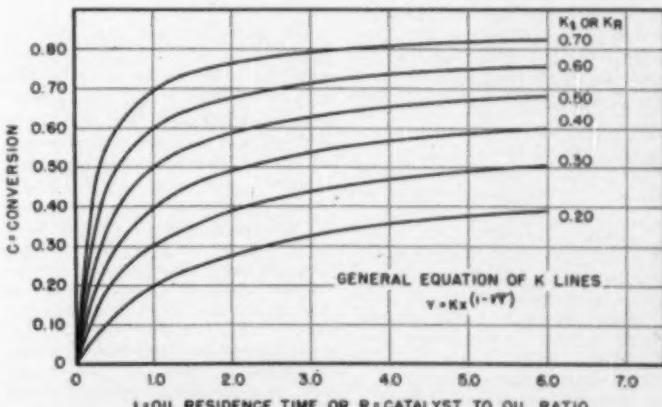


Fig. 5. Conversion vs. Oil-Residence Time or Catalyst-to-Oil Ratio.

where:

$C$  = conversion; volume fraction

$R$  = catalyst-to-oil ratio

$K_R$  = constant for a given feed stock, oil-residence time, reaction temperature and catalyst activity

NOTE:  $K_R$  may be defined as the crackability of the feed stock at a catalyst-to-oil ratio of one and the given conditions of the other TCC variables.

Table 2 summarizes data on catalyst-to-oil ratio that were used in this correlation study. Use of these data, in exactly the same method as outlined above for oil-residence time, yielded the data presented on Figure 4. Again close agreement exists between the actual data and the  $K_R$  line for that feed stock, oil residence time, reaction temperature, and catalyst activity.

**Chart for Both Residence Time and Catalyst-to-Oil Ratio.** Figure 5 is a family of curves derived from the above correlating expressions (Eqs. 4 and 5) for use in studying changes in either oil-residence time or catalyst-to-oil ratio. This chart summarizes the effect of both variables and may be used for either. Use of this chart requires first the knowledge of one set of operating data; that is, the conversion ( $C$ ) obtained for a given oil-residence time ( $t$ ), catalyst-to-oil ratio ( $R$ ), reaction temperature, and feed stock. The value of conversion for the given oil-residence time or catalyst-to-oil ratio establishes a  $K_t$  or  $K_R$  curve for that feed stock and the given operating variables. Movement along this  $K_t$  or  $K_R$  line indicates the effect on conversion of varying either (not both) oil-residence time or catalyst-to-oil ratio while maintaining all other conditions constant. When both catalyst-to-oil ratio and oil-residence time are changed, calculations must be made successively.

Typical example:

Given:

At  $t = 1.0$  and  $R = 2.0$ ,  $C = 0.40$ .

What will  $C$  be at  $t = 2.0$  and  $R = 4.0$ ?

(1) Entering Figure 5 at  $t = 1.0$ , a point in the family of  $K_t$  lines is established. Now move parallel to the adjacent curves to  $t = 2.0$ , at which point  $C = 0.49$ .

(2) Entering Figure 5 at  $R = 2.0$ , a point in the family of  $K_R$  lines is established. Now move parallel to the adjacent curves to  $R = 4.0$ , at

which point  $C = 0.565$ , the final answer.

The same result would be obtained if the change due to  $R$  were calculated first.

### Definitions

**Conversion** is the volume fraction or volume per cent of the original gas oil charge converted to gas, gasoline and coke.

**Oil-Residence Time** is the time in hours required for a volume of liquid oil, equivalent to the volume of catalyst in the reactor, to pass through the reactor.

**Space Velocity** is the reciprocal of oil-residence time.

**Catalyst-to-oil Ratio** is the ratio of the volume of catalyst being circulated to the volume of liquid oil being charged per unit time.

### Acknowledgment

Thanks are extended to both the Houdry Process Corp. and Union Oil Company of California for data used herein, and permission to publish this article. Authors point out that previous work by development engineers of the Union Oil Co. and Houdry Process Corp. served as a basis and background for this work.

### Discussion

**B. W. Neumair (Richfield Oil Corp., Wilmington, Calif.):** This is a rather novel approach in relating the effects of space velocity and catalyst-to-oil ratio to conversion in Thermofoor Catalytic Cracking.

The particular advantage that is apparent in the empirical formulas seems to be the ability to extrapolate with more reliability and with a minimum amount of data. We applied some Richfield pilot plant data to the two formulas and obtained reasonably close agreement with them. Slight changes in the exponential factors in the case of the space velocity formula (one minus the cube root of conversion rather than one minus the square root of conversion) seems to fit our data better. Also in the case of the catalyst-to-oil ratio formula (we didn't have data beyond four to one catalyst-to-oil ratio), the exponential factor which fit our data better was one minus conversion, rather than one minus the square root of conversion. It seemed rather odd that the

two variables effecting conversion could be handled in much the same way; in fact, with identical formula type.

I believe it is generally accepted that the major effect of catalyst-to-oil ratio is that of contributing improved catalyst activity to the reaction zone and because of that would possibly have a limiting terminal condition which would not allow 100% conversion by that factor alone.

**R. L. Flanders (California Research Corp., Berkeley, Calif.):** In general, the data appear reasonable and consistent with findings in both our pilot and commercial units. Since space rate and catalyst-to-oil ratio are not varied over a wide range in commercial practice at Richmond, a check on the extremities of the correlation was not possible.

The pilot cracking equipment at Richmond has been used primarily to evaluate cracking characteristics of different feed stocks by cracking at constant operating conditions in a fixed-bed Houdry unit. The process yield data available, however, show reasonable agreement with those presented in the paper.

**A. L. Conn (Standard Oil Co., Ind., Whiting, Ind.):** A question in my mind has to do with the use of oil contact time and space velocity interchangeably. In our early work with fixed bed catalytic cracking, we found that the conversions obtained did not correlate nearly as well with oil contact time as with space velocity. This was demonstrated by the fact that using large quantities of steam, which greatly reduced the oil contact time but did not change the space velocity, had little effect upon conversion. Was any steam present in the work presented, or does the oil contact time assume no steam?

**R. A. McKean:** Well, on the question on oil contact time, as we use it, it's very simple. It is the inverse, or 1 over the space velocity. To express it another way, it's the ratio of catalyst volume to oil charge rate. As we use it, oil-residence time is not time at all, although its units are time.

As far as steam is concerned, if we had steam in one of these runs, we had the same quantity in another. Now what would happen if we tried to compare a given oil contact time, which of course is based on cold oil charging rate, with another where the quantity of steam has been varied, I don't know.

*(Presented at Tenth Regional Meeting, Los Angeles, Calif.)*

# RATE OF SULFONATION OF BENZENE WITH SULFURIC ACID

R. C. CROOKS and ROBERT R. WHITE

University of Michigan, Ann Arbor, Michigan

The rate of sulfonation of benzene at a fugacity of one atmosphere by sulfuric acid was determined in a steady flow apparatus at temperatures from 90 to 140° C. in reaction mixtures containing from 2.53 to 41.83 wt. %  $C_6H_5SO_3H$ , and from 49.17 to 81.53 wt. %  $H_2SO_4$ . Mass-transfer effects were eliminated by maintaining high agitator speeds. These data and previous data on the sulfonation of benzene were correlated by the equation

$$\frac{R_L}{C_A} = 118 \left[ x_A - \frac{1}{2} x_W + \frac{1}{4} x_S \right]^{-0.239 + \frac{5319}{T}}$$

The method of correlation was also applied to previous data on the nitration of toluene at 95° F. (10) giving the relation

$$\frac{R_N}{C_N} = 2.52 \times 10^6 \left[ x_T + \frac{5}{3} x_A - \frac{1}{3} x_W \right]^{0.08}$$

SULFONATION of benzene is representative of a large class of reactions which have widespread industrial application. While the mechanism of the reaction has been the subject of many investigations (6, 7, 9, 11, 14, 15, 17), there are only a few limited and somewhat unsatisfactory data on the rate at which the reaction proceeds (2, 8, 19). This investigation was undertaken to determine the effect of temperature and the composition of the reactants on the rate of sulfonation of benzene.

**Experimental Equipment.** A steady-state-flow method was chosen in preference to the batch method in order to avoid the uncertainties inherent in the differentiation of the composition-time data derived from batch experiments. Benzene has but a limited solubility in sulfuric acid solutions, its concentration is difficult to determine quantitatively, and representative samples of the reac-

tion solutions are difficult to obtain because of vaporization during sampling. It was decided to maintain the fugacity of benzene in the reacting system at a constant value by bubbling benzene vapor at a known pressure through violently agitated sulfuric acid solutions.

The equipment in which this was accomplished is shown schematically in Figure 1. Benzene and sulfuric acid reactants are fed continuously from constant-head-type reservoirs *A* and *B*, through flowmeters *D* and *E*. Benzene liquid passes from the hydrostatic leg *E* into the vaporizer *F*, and vaporized benzene is introduced into the bottom of the reaction cell *O* through the insulated and electrically heated line *J*. Flask *G* is employed as a liquid trap to prevent unvaporized benzene from entering the reaction cell. Flask *H* includes a hydrostatic seal and serves to prevent the formation of a vacuum, in the benzene vapor system when the equipment cools. Both flasks are insulated and electrically heated.

The level of the mixture of liquid and vapor in the reaction cell is established by the position of the liquid overflow outlet. The liquid product overflows through the side outlet into a *U*-tube,

from which it is withdrawn by a siphon tube whose outlet is immersed in the liquid seal cup *U* located outside the bath. The product then flows through a side outlet from the siphon seal into the product receiver *W*. Excess benzene vapor, released from the reaction mixture in the cell, passes through the insulated and electrically heated line *L* to the condenser *AA*, and the condensate is collected in the benzene receiver *X*.

A copper-constantan thermocouple *Q*, in a well immersed in the reaction liquid measures the temperature in the reaction cell. The dibutyl phthalate bath *N* is electrically heated and thermostatically controlled to maintain the desired temperature in the reaction cell.

The reaction cell is constructed of pyrex glass; details are shown in Figure 2. Benzene vapor entering the cell through the bottom tube connection is subdivided into small bubbles by the shearing forces present at the ends of the rotating distributor tubes.

Calibrated constant-head-type reservoirs as shown in Figure 1 having a capacity of 5,000 ml. are employed as a source and measure of benzene and sulfuric acid reactants. The adjustable level of the open tube in the reservoir establishes the hydrostatic pressure causing liquid movement by fixing the pressure at the inlet of the siphon tube. Pyrex glass capillary tube flowmeters were used to indicate instantaneous flow rates of benzene and sulfuric acid reactants to the reaction cell.

An aspirator arrangement, shown in Figure 3 is used to obtain reaction mixture samples directly from the reaction cell. A 125-ml. Erlenmeyer flask, with a side tube added, was connected to a glass-sampling tube which extended to within the reaction mixture in the cell. The 1-gal. bottle with a water siphon functioned to aspirate a liquid reaction mixture sample from the cell into the sampling bottle.

NOTE: Details of the analytical methods and procedures (Appendix I) are on file (Document 2752) with the American Documentation Institute, 1719 N Street, N.W., Washington 6, D.C. Data obtainable by remitting 50 cents for microfilm and 60 cents for photocopies.

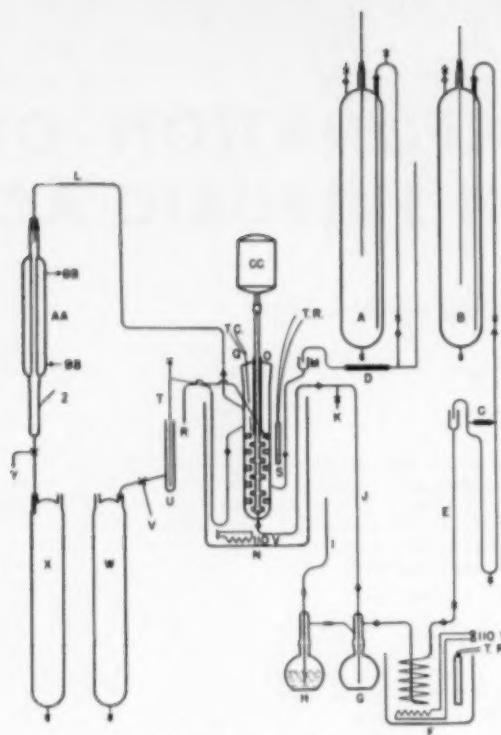


Fig. 1. Schematic Diagram of Equipment.

## Materials

*Sulfuric Acid.* Reagent grade C.P. sulfuric acid manufactured by the General Chemical Co. was mixed with distilled water to the various concentrations desired for acid reactant solutions.

**Benzene.** A technical grade benzene manufactured by The Barrett division, Allied Chemical and Dye Corp., was used as reactant. Its freezing point was determined to be 5.28°C., compared with a value of 5.51°C. determined on pure benzene (17). The benzene purity indicated by the freezing point lowering was 99.65% benzene, expressed on a mole basis.

*Experimental Procedure.* In each experimental run, the reaction process is conducted under conditions of constant reactant feed rates, compositions, and reaction mixture temperatures, for a period of time sufficient for a steady-state condition in the cell to be attained.

The reaction is maintained under conditions of constant temperature and feed rates of reactants for a period of from 1½ to 5 hr., depending on the rates of flow of the reactants to attain steady-state operating conditions in the reaction mixture. There is an appreciable difference

on the condensate line below the condenser (*Y*, Fig. 1). The cell liquid sample was obtained by aspirating approximately 30 ml. of the reaction mixture through line *R*, Figure 1, into an Erlenmeyer flask as illustrated in Figure 3. In order to stop the progress of the reaction, a predetermined quantity of distilled water sufficient to stop all reaction is previously pipetted into the flask. After the cell sample is taken, the volume of liquid phase present in the cell reaction mixture is determined.

### *Analyses*

The following analyses were made:

- A. Reaction mixture withdrawn from the cell
    - 1. Sulfuric acid
    - 2. Benzene sulfonic acid
  - B. Overflow product
    - 1. Sulfuric acid
    - 2. Benzene sulfonic acid
    - 3. Water
  - C. Benzene condensate
    - 1. Water

Details of the analytical procedures are on file with the American Documentation Institute. (See p. 249.)

The water content of the reaction mixture in the cell is difficult to determine by a direct analysis since in order to halt the reaction it is necessary to withdraw the sample into a "flooded" flask as just described above. The addition of a relatively large amount of water to the sample introduced serious errors in the subsequent analysis for water although it does not affect the analysis for sulfuric acid and benzene sulfonic acid. For this reason, an analysis of the overflow product samples withdrawn into a dry bottle is made and the effects of the back-reaction occurring during the sampling operation and the passage of the product through the transfer line is corrected through a stoichiometric balance based on sulfur, between the overflow product sample and the reaction mixture sample. The method of correction is illustrated in Table 1.

TABLE 1.—CORRECTION OF CELL ANALYSIS BY A SULFUR MATERIAL BALANCE

	Cell Analysis	Overflow Analysis	Adjusted Cell Analysis
Wt. % H <sub>2</sub> SO <sub>4</sub>	75.92	75.37	75.87
Wt. % BSA	13.16	13.96	13.15
Wt. % H <sub>2</sub> O	—	11.03	10.94
% Total	—	99.36	99.96
Wt. % S in H <sub>2</sub> SO <sub>4</sub>	24.817	24.637	—
Wt. % in BSA	2.667	2.830	—
% Total	27.484	27.467	—
Correction factor =	27.484	—	0.9994
Adjusted H <sub>2</sub> SO <sub>4</sub> = (75.92) (0.9994) = 75.87%	—	—	—
Adjusted BSA = (13.16) (0.9994) = 13.15%	—	—	—
After reaction Adjustment of H <sub>2</sub> O Concentration:	—	—	—
After reaction decrease in % H <sub>2</sub> SO <sub>4</sub> = 75.87 - 75.37 = -0.50%	—	—	—
Water formed = 0.50 × 18.0	+0.09%	—	—

## Experimental Results

Thirty runs over a temperature range of from 90° C. to 140° C. were made. Sulfuric acid-water solution mixtures in concentrations varying from 80.4% to 95.1% sulfuric acid by weight, were employed as reactant feed solutions. The quantity of benzene vapor introduced into the cell was approximately twelve times the amount which entered the reaction. Benzene sulfonic acid was formed in these runs to concentrations which varied from a minimum of 2.53% to a maximum of 41.83% by weight.

Experimental errors present in measurements of the quantities observed in this work are estimated to be approximately as follows:

Volumetric rates, %	$\pm 0.5$
Temperature	$\pm 0.05^\circ$ C.
Wt. % H <sub>2</sub> SO <sub>4</sub>	$\pm 0.05$
Wt. % BSA	$\pm 0.2$
Wt. % H <sub>2</sub> O	$\pm 0.05$
Reaction mixture volume	$\pm 3$ ml.

Typical experimental data obtained are shown in Table 2, "Operating Conditions," and Table 3, "Reaction Mixture Analytical Data."

In Table 2, columns 1, 2, 3, and 4 present the run number, reaction temperature, barometric pressure and stirrer speed respectively. Column 5 gives the quantity of the reaction mixture determined from the liquid level in the cell after the flows of the reactants and the stirrer were stopped at the end of the run. The space velocity given in column 6 is the quotient of the hourly volume rate of acid feed and the volume of the liquid phase in the cell (column 5). Columns 7 and 13 give the density of the acid feed and overflow products respectively. Columns 8-12 give the hourly mass-flow rates of the various feed and product streams.

Table 3 presents the typical analyses of the samples. The "Corrected" analysis of the reaction mixture, as explained in Table 1 is presented in columns 12-15. The difference between the total of column 15 and 100 per cent is assumed to be benzene dissolved in the reaction mixture and the "benzene-free" analysis based upon this assumption is reported in columns 16-18.

Table 4 shows typical material balances based on sulfur, oxygen, and ben-

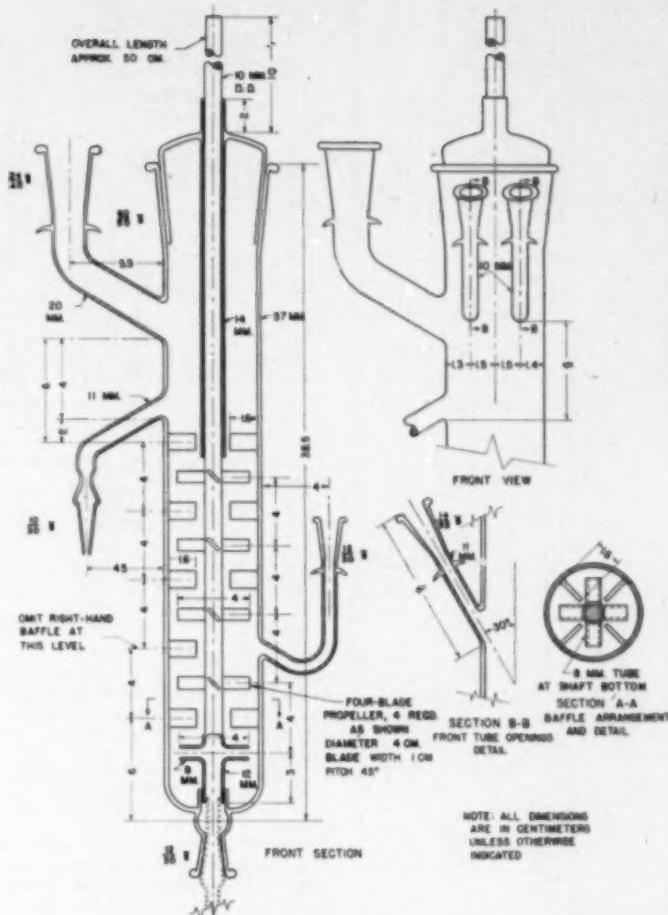


Fig. 2. Reaction Cell.

zene for each run. In nearly all cases, the material balances check to within 1%.

Table 5 presents derived values employed in correlating the data. Product densities (column 4) at the reaction temperatures were computed from their densities at 25° C. and the experimentally determined volumetric expansion

coefficient of 0.0006 ° C.<sup>-1</sup>. The total moles per liter of reaction mixture (column 9) were computed from the product mole fraction compositions, columns 5-7, and the densities at the reaction temperatures. Reaction rates,  $R_L$ , were calculated from the concentration of benzene sulfonic acid in the product, the mass rate of product formed, the

TABLE 2.—OPERATING CONDITIONS

Run No.	Reaction T., ° C.	Barometer P., mm. Hg.	Stirrer Speed rev./min.	Reaction Liquid Vol. ml.	Space Velocity feed, ml. sec. <sup>-1</sup>	Acid Feed H <sub>2</sub> SO <sub>4</sub> wt. %	Acid Feed			Benzene Feed Rate g./hr.	Benzene Condensate Rate g./hr.	Overflow Product Rate g./hr.	Density at 25° C. g./ml.
							6	7	8	9	10	11	12
11	140	761	1260	324	0.94	95.14	1.830	560	368	208	729	1.560	
12	100	736	1260	311	2.09	95.14	1.826	2194	1060	992	2360	1.616	
13	100	740	1770	263	2.94	95.14	1.826	1012	1078	738	2353	1.612	
14	100	733	650	885	1.55	95.12	1.768	1054	512	570	1049	1.724	
15	140	729	650	355	3.05	95.08	1.822	1986	1028	566	2436	1.597	

TABLE 3.—REACTION MIXTURE ANALYTICAL DATA

Run No.	Reaction Mixture Analysis			Overflow Product Analysis			Reaction Mixture Current Analysis			Reaction Mixture Analytical Results				
	H <sub>2</sub> O <sub>2</sub>	BSA	Sulfur	H <sub>2</sub> O <sub>2</sub>	BSA	Total	Sulfur	H <sub>2</sub> O <sub>2</sub>	BSA	Total	H <sub>2</sub> O <sub>2</sub>	BSA	H <sub>2</sub> O	
2	2	3	6	7	8	10	11	12	13	15	15	17	18	
11	43.47	41.83	24.55	43.39	8.32	59.51	24.45	49.17	41.43	8.14	59.14	48.60	42.19	
12	64.79	37.64	36.78	62.78	29.56	7.20	59.64	36.51	64.13	27.26	7.16	58.65	68.01	72.73
13	64.52	28.18	26.80	62.98	29.57	7.25	59.20	26.29	63.51	27.74	7.15	58.40	64.54	78.19
14	78.92	6.13	27.64	78.98	6.01	10.15	59.92	26.96	78.70	6.11	15.11	59.92	78.77	91.11
15	79.42	26.02	25.74	55.52	36.56	8.02	59.90	25.50	55.87	25.67	7.98	59.52	56.14	35.84
														8.02

Weight For Const.

Run No.	Reaction Mixture Analysis			Overflow Product Analysis			Reaction Mixture Current Analysis			Reaction Mixture Analytical Results			
	H <sub>2</sub> O <sub>2</sub>	BSA	Sulfur	H <sub>2</sub> O <sub>2</sub>	BSA	Total	Sulfur	H <sub>2</sub> O <sub>2</sub>	BSA	Total	H <sub>2</sub> O <sub>2</sub>	BSA	H <sub>2</sub> O
11	180.3	181.3	384.9	181.3	684.1	1456.7	1267.3	1456.9	1079.8	1077.5	1078.6	986.7	1076.1
12	682.4	594.5	1267.3	682.4	594.5	1267.3	1267.3	1267.3	1077.5	1077.5	1079.7	1079.7	1079.7
13	504.5	295.6	724.9	504.5	295.6	724.9	724.9	724.9	731.0	731.0	811.7	803.0	803.0
14	295.3	617.1	831.0	295.3	617.1	831.0	831.0	831.0	1086.5	1086.5	1026.2	1026.2	1026.2

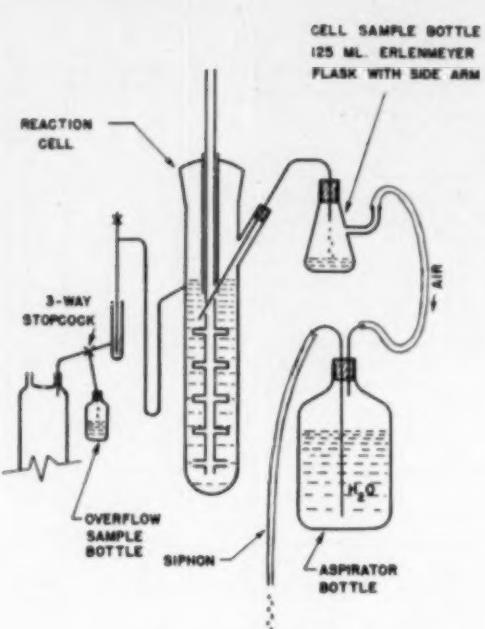


Fig. 3. Sampling Method.

volume of reaction mixture in the cell and the molecular weight of benzene sulfonic acid, 158.17, according to the relation

$$R_L = \frac{(\text{wt. \% BSA})(\text{mass hourly product rate})}{(100)(\text{volume of the reaction mixture}) (158.14)}$$

Values for  $(R_L/C_A)_{\text{min}}$  were computed from the empirical equation used to correlate the data, where  $C_A$  is the concentration of sulfuric acid in the product expressed as moles per liter.

#### Comment

**Mass Transfer Effects.** Since sulfuric acid is relatively nonvolatile, the reaction between benzene and sulfuric acid must occur in the liquid phase of the reaction mixture; the vapor phase consists primarily of benzene and small concentrations of water, as indicated by the analyses of the benzene condensate stream.

Presumably the rate of sulfonation of benzene in the liquid phase depends upon

the fugacity of benzene in the liquid phase in addition to other variables, so that the correlation of the sulfonation

rates requires a knowledge of the effective benzene fugacity in the liquid phase. In this investigation, sufficient agitation was used so that the fugacity of benzene in the liquid phase may be taken as substantially 1 atm., the fugacity of benzene in the gas phase.

In order to establish the fact that sufficient agitation was used, Runs 30, 14, 16, and 10 were made at agitator speeds of 0, 650, 1260, and 1770 rev./min. respectively, the composition of the reaction mixture, the temperature and space velocity being held constant and so chosen as to produce a high rate of reaction in order to emphasize any mass-transfer effects. The rate of sulfonation for these runs is shown as a function

TABLE 4.—RUN MATERIAL BALANCES

g./hr.

Run No.	Sulfur		Oxygen		Benzene	
	In	Out	In	Out	In	Out
11	180.3	181.3	384.9	384.9	287.5	286.7
12	682.4	684.1	1456.7	1456.9	1079.8	1076.1
13	504.5	594.5	1267.3	1267.3	1077.5	1079.7
14	295.3	295.6	724.9	724.9	811.7	803.0
15	617.1	631.0	1819.0	1819.0	1086.5	1026.2

TABLE 5.—CORRELATION SUMMARY

Run No.	Reaction Temp., °C.	At React., °F.	Product Mole Fraction				Mole BSA (W <sub>2</sub> /L)	$\frac{R_t}{O_2}$ observed	$\frac{R_t}{O_2}$ calcd	Reaction Rate
			H <sub>2</sub> O <sub>2</sub>	BSA	$\frac{H_2O}{S_2}$	$\left[ \frac{x_2 - 1}{x_2 - 2} \frac{x_2}{x_2 + 4} x_2 \right]_{O_2/L}$				
1	3	40	1.695	1.517	0.4483	0.1873	0.3475	0.3860	0.3861	4.07
1	100	1.696	1.516	0.5063	0.5063	0.5063	0.3414	0.3586	0.3447	0.470
2	100	1.693	1.513	0.5063	0.5063	0.5063	0.3414	0.3586	0.3447	0.470
3	100	1.693	1.513	0.5063	0.5063	0.5063	0.3414	0.3586	0.3447	0.470
4	100	1.691	1.513	0.5063	0.5063	0.5063	0.3414	0.3586	0.3447	0.470
5	100	1.691	1.513	0.5063	0.5063	0.5063	0.3414	0.3586	0.3447	0.470
6	140	1.592	1.489	0.4116	0.1893	0.5802	0.2991	0.344	0.344	4.07
7	140	1.591	1.488	0.4116	0.1893	0.5802	0.2987	0.344	0.344	4.07
8	140	1.591	1.488	0.4116	0.1893	0.5802	0.2987	0.344	0.344	4.07
9	140	1.591	1.488	0.4116	0.1893	0.5802	0.2987	0.344	0.344	4.07
10	140	1.591	1.488	0.4116	0.1893	0.5802	0.2987	0.344	0.344	4.07
11	140	1.590	1.489	0.4117	0.1712	0.2711	0.204	0.1792	0.1792	0.817
12	100	1.696	1.516	0.5063	0.5063	0.5063	0.3414	0.3586	0.3447	0.470
13	100	1.692	1.512	0.5062	0.5062	0.5062	0.3413	0.3585	0.3446	0.469
14	100	1.724	1.635	0.4769	0.4457	0.4246	0.3536	0.3730	0.3730	3.111
15	140	1.597	1.494	0.4101	0.1876	0.5802	0.2977	0.2777	0.2777	0.817
16	140	1.590	1.488	0.4116	0.1893	0.5802	0.2987	0.344	0.344	4.07
17	100	1.693	1.513	0.5063	0.5063	0.5063	0.3414	0.3586	0.3447	0.470
18	100	1.621	1.551	0.5068	0.5068	0.5068	0.3413	0.3585	0.3446	0.469
19	100	1.698	1.513	0.5068	0.5068	0.5068	0.3413	0.3585	0.3446	0.469
20	100	1.710	1.636	0.5284	0.5284	0.5284	0.4146	0.4246	0.4246	0.484
21	100	1.692	1.510	0.5062	0.5062	0.5062	0.3413	0.3585	0.3446	0.469
22	100	1.747	1.672	0.4979	0.4447	0.4141	0.4313	0.3901	0.3901	0.205
23	140	1.694	1.549	0.4440	0.4440	0.4440	0.4142	0.4879	0.4879	0.114
24	140	1.701	1.691	0.4157	0.4157	0.4157	0.4058	0.4976	0.4976	0.116
25	120	1.705	1.613	0.4192	0.4192	0.4192	0.4055	0.4934	0.4934	0.098
26	120	1.707	1.615	0.4190	0.4190	0.4190	0.4050	0.4934	0.4934	0.098
27	120	1.692	1.577	0.4985	0.4799	0.4436	0.4045	0.4844	0.4844	0.098
28	120	1.614	1.387	0.4935	0.4833	0.4433	0.4033	0.4844	0.4844	0.098
29	90	1.630	1.646	0.5218	0.4433	0.3997	0.4045	0.4844	0.4844	0.098
30*	140	1.628	1.552	0.5060	0.5060	0.5060	0.3413	0.3585	0.3446	0.469
31	90	1.741	1.676	0.4901	0.4901	0.4901	0.4045	0.4934	0.4934	0.098

\* Reaction liquid in Run No. 30 was not saturated with benzene.

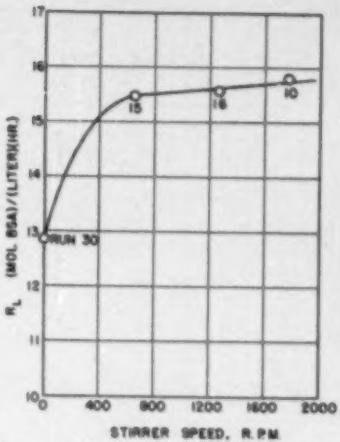


Fig. 4. Effect of Agitation Upon Rate of Reaction.

of stirrer speeds in Figure 4. This figure shows that the rate of reaction is substantially independent of stirrer speed over a range of 650 to 1770 rev./min., indicating that above 650 rev./min. the fugacity of benzene in the reaction mixture is substantially constant at its value of 1 atm. in the gas phase. A similar effect has been noted previously in the nitration of toluene (10).

**Diphenyl Sulfone.** The reaction between benzene and sulfuric acid to produce benzenemonosulfonic acid did not produce by-products under the conditions employed in these experiments. The normal by-product, diphenyl sulfone, was shown by Harvey (8) to appear only when the reaction had proceeded nearly to completion and the benzenemonosulfonic acid concentration had exceeded values of about 80% by weight. The absence of sulfone formation in these experiments was indicated by the lack of precipitation when product samples were diluted with water; diphenyl sulfone is but slightly soluble in water.

**Benzenedisulfonic Acid.** The presence of disulfonic acids was tested by preparing a barium salt of the sulfonic acid formed in Run 30, and analyzing the barium sulfate salt for barium content. The barium content of the sulfonic acid salt preparation was determined to be 29.31% Ba. This compares favorably with the barium content of the barium monosulfonate monohydrate. The barium content of the barium sulfate formed from Run 30 product is compared in Table 6 with the calculated

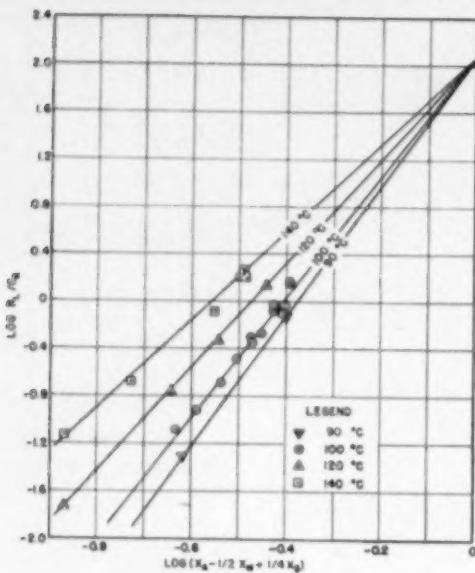


Fig. 5. Reaction Rate—Composition Correlation.

TABLE 6.—BARIUM CONTENTS OF SULFONATE SALTS

Salt	% Barium by Weight
Sulfonic acids of Run 30	29.0
Ba(O <sub>2</sub> S <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> · H <sub>2</sub> O	29.35
Ba(O <sub>2</sub> S <sub>2</sub> H <sub>5</sub> ) <sub>2</sub>	30.41
Ba(O <sub>2</sub> S <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> H <sub>2</sub> O	36.77

barium contents of other barium sulfonates.

#### Correlation of Benzene Sulfonation Rates

#### Composition Correlation. Experimental

TABLE 7.—BATCH SULFONATION DATA (HARVEY (8))

T, °C. (1)	Reaction Time, min. (2)	Mole Fraction				$R_L$ $C_A$ (7)	$R_L$ $C_A$ (8)
		H <sub>2</sub> SO <sub>4</sub> $x_A$ (3)	H <sub>2</sub> O $x_w$ (4)	BSA $x_B$ (5)	Sulfone $x_P$ (6)		
AB	0	.715	.285	0	0	...	...
	270	.304	.371	.325	0	.160	.0357
	420	.255	.332	.413	0	.167	.0482
	570	.157	.551	.592	0	.175	.0975
	690	.110	.572	.717	.001	.184	.1622
	825	.087	.490	.708	.005	.194	.226
140	180	.326	.345	.329	0	.225	.0481
	280	.220	.287	.513	0	.249	.0914
	400	.155	.248	.597	0	.277	.1560
	520	.0968	.155	.747	.001	.317	.334
	700	.0364	.0786	.878	.007	.480	1.469
	740	.152	.255	.593	0	.375	.444
150	305	.0946	.159	.746	0	.665	.705
	375	.0672	.115	.815	.0026	.545	.901
	465	.0194	.0995*	.951	.0196	.415	2.58
	710	.0182	.0694	.919	.0530	.225	1.52
	150	.232	.388	.379	.0005	.497	.148
160	210	.138	.238	.621	.0026	.649	.416
	274	.0668	.152	.756	.0052	.646	.967
	360	.0176	.084*	.869	.0294	3.37	21.2
	467	.0147	.087*	.791	.1072	2.92	23.0
	180	.108	.199	.690	.0033	.885	.782
170	300	.0120	.069*	.919	.060	5.78	.591
	360	.0103	.069*	.822	.159	5.72	.70.0
	450	.0116	.010*	.772	.207	4.25	46.4
	540	.0116	.010*	.703	.275	3.33	38.1

\* Water weight percentage values were reported as < 0.20%.

tal rates of reaction between benzene and sulfuric acid in solutions having a benzene fugacity of 1 atm. correlate as a function of reaction system composition and temperature. Figure 5 shows values of  $\log R_L/C_A$  plotted against the corresponding values of  $\log (x_A - \frac{1}{2}x_w + \frac{1}{4}x_o)$ . In this plot, the values for the rates of reaction measured at a common temperature lie close to a straight line, which may be used to express a functional relationship between the rate of reaction and the solution composition.

Each temperature line may be represented by the equation

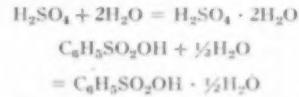
$$\log \frac{R_L}{C_A} = b \log (x_A - \frac{1}{2}x_w + \frac{1}{4}x_o) + \log I, \quad (1)$$

which reduces to the form

$$R_L = I(x_A - \frac{1}{2}x_w + \frac{1}{4}x_o)^b C_A, \quad (2)$$

where  $\log I$  is the intercept at  $\log (x_A - \frac{1}{2}x_w + \frac{1}{4}x_o)$  equal to zero;  $b$  represents the slope and is a function of temperature.

The composition function ( $x_A - \frac{1}{2}x_w + \frac{1}{4}x_o$ ) may be regarded as "anhydrous"  $H_2SO_4$  on the basis of the hydration reactions

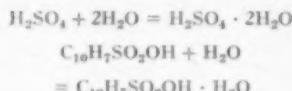


All water present is assumed to enter into hydration reactions. In these reactions, the benzene sulfonic acid is regarded as a dehydrating reagent, reacting with water to form the hemihydrate. The remaining water is regarded as combined with the sulfuric acid to form the double hydrate. The remaining sulfuric acid may then be viewed as being in the anhydrous form, and its mole fraction represented by the function ( $x_A - \frac{1}{2}x_w + \frac{1}{4}x_o$ ).

In product-free solutions, the dependence of the reaction rate upon the composition function ( $x_A - \frac{1}{2}x_w + \frac{1}{4}x_o$ ) is in agreement with the "pi-value" concept defined by Guyot (7), and evaluated more extensively by others (6) as the limiting value of sulfuric acid concentration below which the reaction will not proceed. For the sulfonation of benzene this value has been determined as approximately 74% by weight of sulfuric acid. This value corresponds

stoichiometrically to the dihydrate  $\text{H}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$ , and is equivalent to a zero value for the composition function  $(x_A - \frac{1}{2}x_w + \frac{1}{4}x_s)$  in product-free solutions. From Figure 5, it is evident that as the composition function  $(x_A - \frac{1}{2}x_w + \frac{1}{4}x_s)$  approaches zero, the specific reaction rate likewise extrapolates to a zero value.

The presence of the benzene sulfonic acid product increases the rate of reaction by combining with some of the water present in the system, thus increasing the effective concentration of the anhydrous sulfuric acid reactant. This is in agreement with Spryskov (15), who sulfonated naphthalene with sulfuric acid to give spent acid concentrations as low as 40.3% at 100°C. and 25% at 162°C., which are far below the pi-values of 65% and 63.7%, respectively, previously established. Spryskov concluded that hydration reactions occurred between water and the sulfuric and sulfonic acids, as



The naphthalene sulfonic acid apparently increased the effective concentration of sulfuric acid by combining with water to form a hydrate.

*Composition - Temperature Correlation.* In a sulfonation system of constant composition, the reaction velocity coefficient,  $k$ , was found to follow the Arrhenius temperature relationship

$$\log k = \frac{A}{T} + B \quad (3)$$

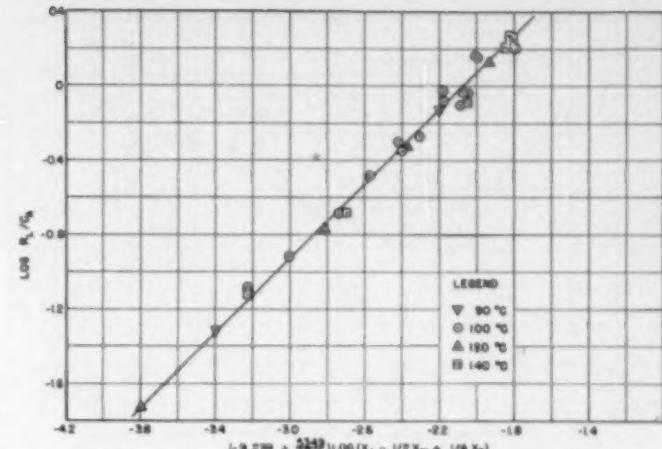


Fig. 6. Reaction Rate—Composition—Temperature Correlation.

where Equation (2) is written as

$$R_L = kC_A \quad (4)$$

$$\log \frac{R_L}{C_A} = \left( -9.239 + \frac{5349}{T} \right) \log (x_A - \frac{1}{2}x_w + \frac{1}{4}x_s) + 2.07 \quad (5)$$

or

$$R_L = 118(x_A - \frac{1}{2}x_w + \frac{1}{4}x_s)^{-9.239 + \frac{5349}{T}} \cdot C_A \quad (6)$$

or

$$R_L = 118e^{\left( -9.239 + \frac{5349}{T} \right)} \ln (x_A - \frac{1}{2}x_w + \frac{1}{4}x_s) \cdot C_A \quad (7)$$

lent to the four temperature lines shown on Figure 5. This line is represented by the equation

Figure 6 shows the experimental specific reaction rates plotted against a combined function of temperature and reaction mixture composition. The straight line drawn through the experimental points on this figure is mathematically equivalent to the four temperature lines shown on Figure 5. This line is represented by the equation

A comparison of the calculated and the observed values for  $R_L/C_A$  is listed in Table 5. The mean deviation for the 30 runs (not including Run 30) is 8.5% between the calculated and observed values.

*Harvey's Sulfonation Data (8).* Data of this investigation cover a space velocity range of 0.76 to 3.99 reciprocal hours. Harvey (8) made batch sulfonations of benzene by sulfuric acid for periods ranging from 3-12 hr., representing space velocities which can be conservatively estimated as equivalent to 0.08 to 0.33 reciprocal hours. The batch data therefore extend to higher degrees of conversion. Although the rates of reaction computed from these batch experiments have large uncertainties, they are useful for order-of-magnitude investigation of some factors in the kinetics of the sulfonation reaction. Table 7 shows the rates of reaction and reaction mixture composition values as computed from Harvey's data. The conversion computed from the batch sulfonation data were graphically smoothed and differentiated to obtain the specific reaction rate values shown in Table 7, columns 7 and 8.

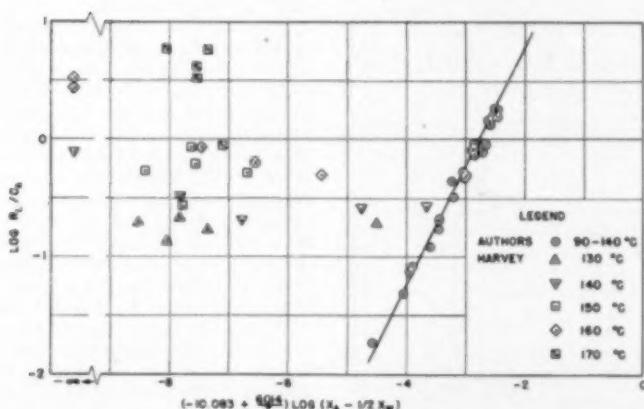


Fig. 7. Correlation Neglecting Effect of Benzene Sulfonic Acid.

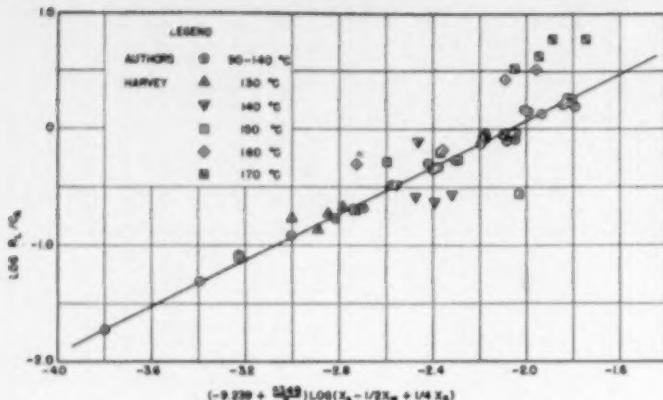


Fig. 8. Correlation Including Effect of Benzene Sulfonic Acid.

**Test of Effect of Benzene Sulfonic Acid on Correlation.** Figures 7 and 8 illustrate the effect of benzene sulfonic acid on the reaction rate correlation. Figure 7 shows that when the benzene sulfonic acid concentration  $x_s$  is not included in the composition function,  $(x_A - \frac{1}{2}x_w)$ , the batch-sulfonation points lie far to the left of the line which correlates the flow data of this investigation. When the sulfonic acid concentration term is included in the composition function, as  $(x_A - \frac{1}{2}x_w + \frac{1}{4}x_s)$ , the batch-sulfonation points straddle the flow-data points as shown in Figure 8. Batch data, representing the higher concentrations of benzene sulfonic acid, indicate that the sulfonic

acid has a significant effect upon the rate of reaction.

**Tests on Order of Reaction.** Tests for first and second orders of reaction with respect to the sulfuric acid component may also be applied to the data; the first- and second-order reactions may be expressed as,

First order:

$$R_L = kC_A \quad (4)$$

Second order:

$$R_L = kC_A^2 \quad (5)$$

Figure 9 shows the experimental points for the specific reaction rates and

the composition function,  $(x_A - \frac{1}{2}x_w + \frac{1}{4}x_s)$ , on the basis of a second-order reaction. It is seen that the batch-reaction points lie definitely above the flow-reaction points, and that the two sets of data are not in agreement when compared on the basis of a second-order reaction. However, the two sets of data do fall together when plotted upon a first-order reaction basis (See Fig. 8).

**Application of Correlation Method to Nitration of Toluene.** As a test of the method by which the benzene sulfonation rates of reaction were correlated, a similar viewpoint was applied to a similar type of reaction—mononitration of toluene by a solution mixture of nitric acid, sulfuric acid and water. Experimental data (10) on toluene mononitration at 95° F. was employed for this test.

The reaction rate of toluene nitration is sensitive to comparatively small changes in concentrations of sulfuric acid and water as well as in the prime reactant, nitric acid. Since the action of sulfuric acid is regarded as that of a dehydrating agent, the rate of reaction was considered upon the basis of the effect of hydration reactions upon the solution environment. It was found that when the hydration reactions were assumed as



a composition function  $(x_N + 5/3x_A - 1/3x_w)$  was obtained by which the specific reaction rate could be correlated. If it be assumed that all the sulfuric acid enters into the hydration reaction, and that the remainder of the water reacts with nitric acid, the quantity  $(x_N + 5/3x_A - 1/3x_w)$  might be viewed as representing anhydrous nitric acid.

In the nitration of toluene, the specific reaction rate  $R_N / x_T C_N$  plots nearly as a straight line against the quantity  $(x_N + 5/3x_A - 1/3x_w)$  on a log-log plot, as shown in Figure 10. At the higher and lower values for the specific rates of reaction, the points fall above a line which represents the data over the major portion of the chart. These particular values represent measurements made at the lowest and highest concentrations of nitric acid employed. Points lying above  $\log (x_N + 5/3x_A - 1/3x_w)$  equal to -0.51 represent reactions in solutions having nitric acid concentrations below 0.30% by weight. The reason that they lie above the line might be found in the difficulty of accurately determining small quantities of nitric acid. The points lying below

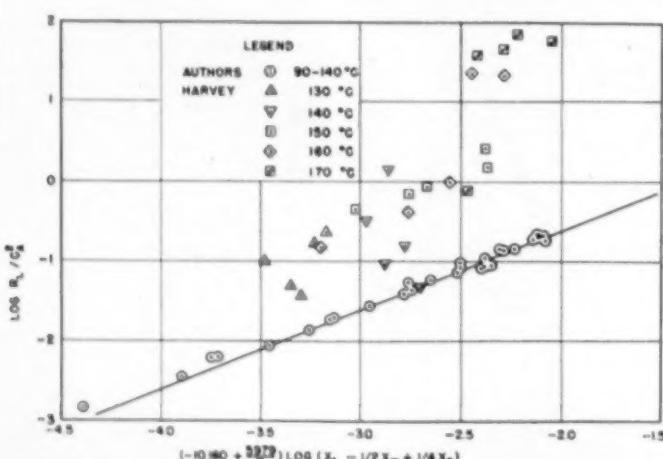


Fig. 9. Correlation Based on Second-Order Reaction.

$(x_N + 5/3x_A - 1/3x_W)$  equal to -0.95 represent the reactions conducted at high concentrations of nitric acid and low concentrations of sulfuric acid.

From Figure 10, the rate of mononitration of toluene at 95° F. may be expressed as

$$\log \frac{R_N}{x_T C_N} = 8.08 \log (x_N + 5/3x_A - 1/3x_W) + 6.40 \quad (9)$$

or

$$R_N = 2,520,000 (x_N + 5/3x_A - 1/3x_W)^{8.08} x_T C_N \quad (10)$$

This equation represents the nitration data over a range corresponding to a ratio of 2500 to 1 in the value of the specific reaction rate  $R_N/x_T C_N$ . Unfortunately insufficient data are available to determine the effect of temperature accurately.

### Conclusions

As a result of this investigation it appears that the concept of anhydrous sulfuric acid is helpful in correlating the rates of sulfonation of aromatic hydrocarbons and that a similar concept may be applied in correlating nitration reactions. Rates of sulfonation are exceedingly sensitive to the composition of the reaction mixture as indicated by Equation 6. The correlation of the data agrees with the form suggested by theoretical considerations. Since mass-transfer effects have been eliminated, the rate correlation applies for the chemical reaction alone and should be generally applicable.

### Notation

$A$  = component  $A$

$B$  = component  $B$

$BSA$  = benzenemonosulfonic acid

$C_A$  = concentration of  $H_2SO_4$  in reaction mixture, mole/l.

$C_N$  = concentration of  $HNO_3$ , moles  $HNO_3$ /l. acid phase

$H$  = enthalpy

$I$  = constant

$K$  = thermodynamic equilibrium constant

$k$  = specific reaction rate coefficient

$MNT$  = mononitrotoluene

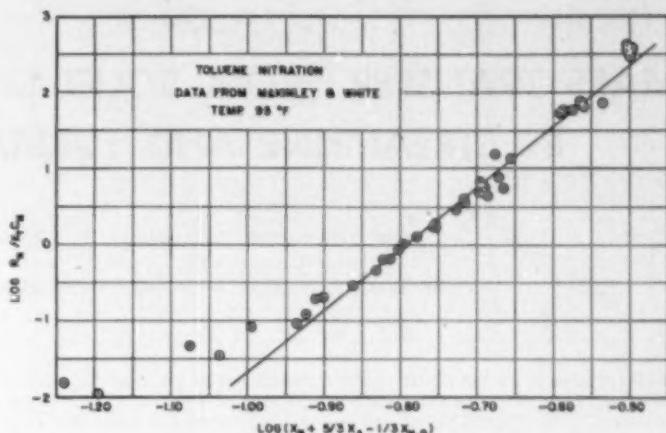


Fig. 10. Rate of Mononitration of Toluene.

$R_L$  = rate of benzene sulfonation, mole BSA/(hr.) (l.)

$R_N$  = rate of toluene nitration, mole  $MNT$ /(hr.) (l. of acid phase)

$r$  = reaction rate, mole/(unit vol.) (unit time)

$T$  = absolute temperature, °K.

$T$  = temperature, °C.

$v_m$  = average molar volume

$x_A$  = mole fraction  $H_2SO_4$ , benzene-free basis in sulfonation

$x_A$  = mole fraction  $H_2SO_4$ , acid phase, in nitration

$x_N$  = mole fraction  $HNO_3$  in acid phase

$x_P$  = mole fraction diphenyl sulfone, benzene-free basis

$x_B$  = mole fraction benzene sulfonic acid, benzene-free basis

$x_T$  = mole fraction toluene in organic phase, on acid-free basis

$x_W$  = mole fraction water

$\gamma_A, \gamma_B$  = activity coefficients of components  $A$  and  $B$

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# MASS TRANSFER FROM SOLID SHAPES TO WATER IN STREAMLINE AND TURBULENT FLOW

W. H. LINTON, JR.,<sup>†</sup> and T. K. SHERWOOD

Massachusetts Institute of Technology, Cambridge, Massachusetts

In order to explore the effect of the Schmidt group on mass transfer in turbulent flow, data were obtained on the rate of solution of cast tubes, cylinders, plates, and spheres of benzoic acid, cinnamic acid, and beta-naphthol. Test objects were placed in water and tests obtained in both streamline and turbulent flow.

Data at low water velocities agree well with the theory for streamline flow. In turbulent flow, good agreement was obtained with the Chilton-Colburn prediction involving the 2/3 exponent on the Schmidt group. In view of the fact that the new data represent a 1000-fold extension of the experimental range of the Schmidt group, this agreement is considered to be quite remarkable.

HEAT transfer, mass transfer, and fluid friction are exceedingly important phenomena in many fields of technology, especially in chemical and process engineering. Data on friction or transfer from a solid surface to a moving fluid have been collected and correlated over the years, and useful empirical equations relating dimensionless groups of the principal variables are now available for most cases of practical importance. For the important case of turbulent flow inside a round pipe the usual dimensionless groups involved are the following:

Heat transfer	$\frac{h}{CG}$	$\frac{DV\rho}{\mu}$	$\frac{Ca}{k}$	$\frac{L}{D}$	$\frac{e}{D}$
Mass transfer	$\frac{k_L}{V}$	$\frac{DV\rho}{\mu}$	$\frac{R}{\rho D_L}$	$\frac{L}{D}$	$\frac{e}{D}$
Fluid friction	$\frac{f}{2}$	$\frac{DV\rho}{\mu}$	$\frac{R}{\rho D_L}$	$\frac{L}{D}$	$\frac{e}{D}$

Other dimensionless groups sometimes employed, such as the Nusselt group, are combinations of those listed.

The similarity of the three processes is suggested in many ways, and the developments of the last 25 years in the theory of turbulence have made it appear likely that there may ultimately be a single theory explaining all three phenomena. The Kármán theory (12) relating heat transfer and friction, for example, was shown by one of the present authors (21) to agree well with data on mass transfer from a tube wall to a turbulent gas stream.

The length and roughness groups,

<sup>†</sup> Present address: DuPont Co., Arlington, N. J.

$L/D$  and  $e/D$ , are of secondary importance in the long smooth tubes used in most commercial equipment, and have received relatively little study. The effect of the Prandtl group  $C\mu/k$  ( $N_{Re}$ ) in heat transfer has been studied over the range from about 0.01 (for certain molten metals) to nearly 100 for hydrocarbons. The corresponding Schmidt group  $\mu/\rho D_L$  ( $N_{Sc}$ ) has not been varied widely in experimental studies of mass transfer.

In 1934 Chilton and Colburn (5) proposed a correlation of the then-ex-

Heat transfer	$\frac{h}{CG}$	$\frac{DV\rho}{\mu}$	$\frac{Ca}{k}$	$\frac{L}{D}$	$\frac{e}{D}$
Mass transfer	$\frac{k_L}{V}$	$\frac{DV\rho}{\mu}$	$\frac{R}{\rho D_L}$	$\frac{L}{D}$	$\frac{e}{D}$
Fluid friction	$\frac{f}{2}$	$\frac{DV\rho}{\mu}$	$\frac{R}{\rho D_L}$	$\frac{L}{D}$	$\frac{e}{D}$

isting heat-transfer data in the form of a graph of

$$j_H = \frac{h}{CG} \left( \frac{C\mu}{k} \right)^{\frac{2}{3}} \text{ vs. } \frac{DV\rho}{\mu}$$

and showed that for the case of round pipes the best line for heat transfer agreed well with the friction data plotted as  $f/2$  vs.  $DV\rho/\mu$ . The success of this correlation prompted them to suggest that mass-transfer data might be correlated in an analogous fashion by means of a plot of

$$j_D = \frac{k_L}{V} \left( \frac{\mu}{\rho D_L} \right)^{\frac{2}{3}} \text{ vs. } \frac{DV\rho}{\mu}$$

Mass-transfer data available at the

time were meager, and were all for cases where  $N_{Re}$  was close to unity. The later data of Gilliland and Sherwood (8) and others confirmed this suggestion in a general way, though the variation in  $N_{Re}$  was extended to cover only the range 0.6 to 2.5. It is also supported by the data of King and Cathcart (14) for a narrow range of diffusivities in liquid systems.

The present investigation was directed to a study of the effect of  $N_{Re}$  on mass transfer by an investigation of systems for which  $N_{Re}$  lay in the range 1000-3000. This involved the measurement of the rate of solution of slightly soluble fused salts from the inner walls of cast tubes through which water was forced in both streamline and turbulent flow. Data were also obtained on the rate of solution of cast plates, cylinders, and spheres of the same materials.

## Experimental Procedure

Two vertical round conduits were employed, one 5.23 and the other 1.90 cm. I.D. In each case the test section was preceded by 75 or more diameters of straight pipe to establish normal velocity gradients in the fluid stream. Test periods were usually one hour, during which the water temperature held constant to within 1° C. in most instances, and always to within 3° C. The city water used was metered to the apparatus by calibrated orifice meters. Water velocity varied from 0.5 to 500 cm./sec. in the tubes, and from 5 to 90 cm./sec. past the other solid shapes. The corresponding Reynolds numbers varied from 230 to 65,000 for the tubes, 3,000 to 180,000 for the plates, and 800 to 10,000 for the cylinders and spheres.

The solutes cast to form the test objects were benzoic acid, cinnamic acid, and beta-naphthol for tubes, benzoic and cinnamic acid for plates and cylinders, and benzoic acid for spheres. The test objects were formed by melting the material and casting in suitable molds. The cast tubes were formed by placing

several short cylinders 0.9 to 7.6 cm. long in the test section, with no appreciable lip or discontinuity between calming section and the first cylinders, or between successive cylinders forming the tube. The short cylinders were carefully dried and weighed before and after the test, and the individual weight loss from each cylinder used to calculate  $k_L$  as a function of the distance downstream from the water inlet. The weight loss in each case was quite small and the diameter of the tube was not increased appreciably. Tests of varying duration showed the rate of solution to reach a steady value after 5 to 10 minutes of operation.

Tests on spheres, cylinders, and flat plates were carried out in the 5.23-cm. conduit. The cast spheres were 1.27 cm. O.D., supported in the center of the channel by a metal wire across the diameter. The cast cylinders were also 1.27 cm. O.D., 3.81 cm. long supported normal to the stream in the 5.23-cm. test section. Metal supports 1.27 cm. in diameter continued the cylindrical shape to the tube walls. Although the water velocity past the center of the cylinder was slightly greater than at the ends, the average water velocity in the test conduit was employed with the cylinder diameter in calculating the Reynolds number.

Thin cast plates 5.23 cm. wide were mounted across the diameter of the 5.23-cm. test section. One or more of these were mounted one behind the other so the total plate length varied from 5.23 to 35.6 cm. The Reynolds number was based on the length of the plate and the average stream velocity.

Values of the molecular diffusivity of benzoic and cinnamic acid in water were obtained in a separate investigation by Chang (4), who employed the diaaphragm cell method over a range of temperatures. Chang's data provided the following values of  $N_{Re}$ :

Temperature, °C.	.....
Benzoic acid	15
Cinnamic acid	20

2590	2320	15	25
1780	1660	1200	970

$D_L$  for beta-naphthol was calculated from the data on tubes of this material with water in streamline flow.

Solubility data on all three compounds were available in the literature but were checked experimentally using cast test objects. (Preliminary data on phenolphthalein were discarded when it was found that its solubility in water varied several fold, depending on the proportions of crystalline and amorphous solid in the cast material.)

## Results

**Streamline Flow in Tubes.** In streamline flow ( $N_{Re} < 2100$ ) no radial mixing occurs, and the transfer of solute from the tube wall into the fluid stream

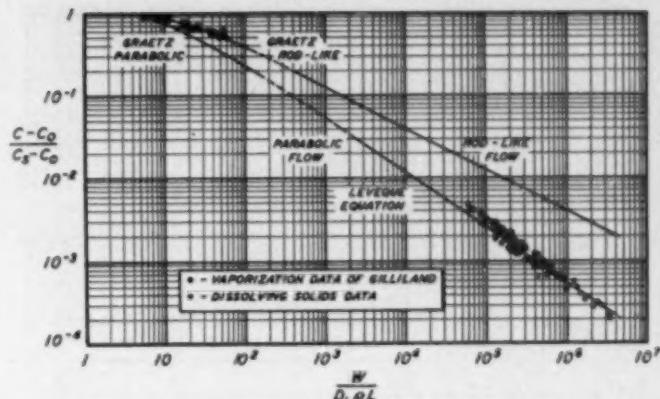


Fig. 1. Data and Theory for Diffusion in Streamline Flow.

is solely by molecular diffusion. For such conditions it is possible to develop a theoretical relationship between the total solution or mass transfer in the tube and the properties of the fluid and solute, tube length and flow rate. This has been done by Graetz, as reported by Drew (6). Graetz gives one equation for the case of a normal parabolic velocity gradient, and a second equation for "rodlike" flow, in which the velocity is assumed constant across the tube diameter. Leveque (15) offers a third equation for flow over a flat plate with a linear velocity gradient in the fluid near the solid surface, and suggested its application to flow in tubes where the conditions are such that the material dissolving penetrates but a short distance into the fluid stream. All three equations involve only the two dimensionless groups  $c - c_0/c_s - c_0$  and  $W/D_L \rho L$ , suggesting the use of these groups in the correlation of experimental data. (Both the Graetz and Leveque equations were derived for heat transfer; the forms applicable to mass transfer

flow, molecular diffusion, and saturation at the solid-liquid interface, as well as the values of  $D_L$  obtained by Chang. It is evident that values of  $D_L$  might be obtained by this experimental technique: the streamline-flow results with betanaphthol were used to obtain the values of  $D_L$  used in correlating the turbulent-flow data with this solute.

Data points appearing in the upper left corner of Figure 1 represent the data of Gilliland and Sherwood (8) for vaporization of liquids in a wetted-wall column at low air rates. These data should presumably fall on the lower theoretical line, and their agreement with the theory for rodlike flow can be considered only as a coincidence.

**Turbulent Flow in Round Tubes.** In addition to the empirical correlation proposed by Chilton and Colburn to relate mass transfer and friction, a number of other methods of correlating mass-transfer data in turbulent flow in tubes has been proposed. These were summarized in 1940 by one of the present authors (21), who showed how the Kármán heat-transfer analogy might be modified for application to mass transfer. More recently Martinelli (19) and Reichardt (20) have developed the theory further. When applied to mass transfer, most of these proposals relate the three dimensionless groups  $k_L/V$ ,  $N_{Re}$ , and  $N_{Sc}$ , and can be compared by means of a graph of  $k_L/V$  vs.  $N_{Re}$  for a fixed value of  $N_{Sc}$ .

It is convenient to compare the present data first with the Chilton-Colburn correlation, by plotting  $j_D$  vs.  $N_{Re}$ . Figure 2 shows the data on benzoic acid, cinnamic acid, and beta-naphthol in 1.90-cm. tubes at an  $L/D$  of 6, plotted in this way. The cumulative  $k_L/V$  was found to fall off slightly as  $L/D$  increased, but to be essentially constant for values of  $L/D$  of 6 or greater. Increase of bulk concentration with  $L/D$  did not affect

follow by inspection.)

Figure 1 shows lines representing the Graetz and Leveque equations, together with a separately derived modification of the Leveque equation for rodlike flow at high values of the abscissa. Experimental data on solution of the three solids check reasonably well with the Leveque equation, which is

$$\frac{c - c_0}{c_s - c_0} = 5.5 \left( \frac{W}{D_L \rho L} \right)^{-\frac{1}{2}} \quad (1)$$

This relation cannot apply at low values of  $(W/D_L \rho L)$ , since the ratio on the left-hand side cannot be greater than unity. The agreement of data and theory supports the assumptions of parabolic

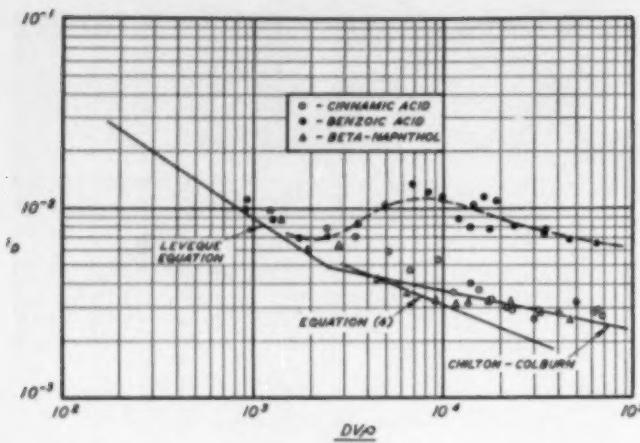


Fig. 2. Results for Turbulent Flow in 1.9-cm. Tube at  $L/D = 6$ .

the driving force, since  $c/c_e$  was always less than 0.005.

Data for beta-naphthol are seen to be in good agreement with the Chilton-Colburn prediction, as are the data for cinnamic acid at the higher Reynolds numbers. Values of  $j_D$  for benzoic acid are nearly threefold greater at high Reynolds, though the points for the three solutes fall together in streamline flow. Similar graphs were obtained for other values of  $L/D$  from 2 to 20.

Figure 3 is a similar graph of results with the 5.23-cm. tube at an  $L/D$  of 6. In this instance, data on cinnamic and benzoic acids agree reasonably well, though both sets of data lie 10 to 60 per cent above the Chilton-Colburn line. Again the two agree in the streamline flow region.

Except for the case of benzoic acid in the smaller tube, the data are in approximate agreement with the Chilton-

Colburn line in the turbulent flow region. The high values for benzoic acid are believed to be the result of surface roughness due to small fissures produced by the irregular solution of small amounts of benzoic acid. Similar difficulties in measuring rate of solution are reported by King and Brodie (13). Benzoic acid is some eight times as soluble as the other two solutes and was the only one of the three to show these fissures, even though small weights of the acid were dissolved. This tendency was more pronounced in the smaller tube, in which the velocity was greater at a given Reynolds number. The benzoic acid curve of Figure 2 will be recognized as having a shape similar to Nikuradse's friction factor curves (1) for artificially roughened pipe.

*Effect of Tube Length.* In the turbulent region the cumulative or average

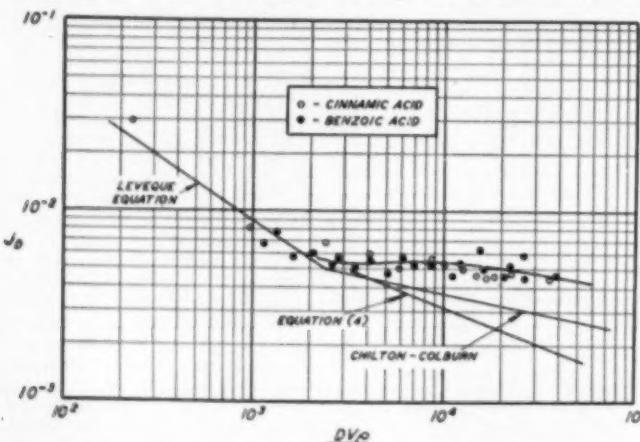


Fig. 3. Results for Turbulent Flow in 5.23-cm. Tube at  $L/D = 6$ .

value of  $j_D$  generally decreased with tube length, although the indicated trend was somewhat variable from run to run (see Table 1) and the typical result was a slightly smaller decrease with increased  $L/D$  than reported by Boelter, Young, and Iversen (3) for heat transfer in a round tube with a long calming section. In most instances, the effect of tube length on  $j_D$  was found to be negligible for values of  $L/D$  greater than about 6. In the streamline region the effect of tube length is important, as indicated by the way the data checked the Leveque equation. The latter may be written (for small values of  $c/c_e$ )

$$j_D = 1.61 \left( \frac{DV\mu}{\mu} \right)^{-\frac{1}{3}} \left( \frac{L}{D} \right)^{-\frac{1}{3}} \quad (2)$$

This suggests a family of lines of  $j_D$  vs.  $N_{Re}$  to the left of  $N_{Re} = 2100$  on Figures 2 and 3, with  $L/D$  as the third parameter. These presumably all connect with the single Chilton-Colburn line, in a manner similar to that suggested by McAdams (17) for heat transfer.

Molecular diffusion in liquids is so slow that for small values of  $L/D$  the dissolved solute will not penetrate the laminar film near the wall and pass into the turbulent core. For such conditions a new relation has been developed, based on an integration of the diffusion equation

$$D_L \frac{\partial^2 c}{\partial y^2} = u \frac{\partial c}{\partial x} \quad (3)$$

It is assumed that the velocity distribution near the wall is that used by Kármán:

$$u = \frac{f^{1/2} \rho y}{2 \mu}$$

and  $f/2$  is taken equal to  $0.023 N_{Re}^{-0.2}$ . The solution obtained may be written

$$j_D = 0.232 \left( \frac{DV\mu}{\mu} \right)^{-0.4} \left( \frac{L}{D} \right)^{-\frac{1}{3}} \quad (4)$$

This is shown on Figures 2 and 3 for  $L/D$  of 6. It agrees with the Chilton-Colburn correlation for  $N_{Re}$  of 10,000 at about  $L/D$  of 4.

From the results shown on Figures 2 and 3 it is evident that the Chilton-Colburn correlation, based on the minus  $\frac{1}{3}$  power of  $N_{Re}$  is substantiated, even though the value of  $N_{Re}$  has been extended to the region of 1000-3000. The effect of  $N_{Re}$  is made evident by Figure 4, which shows various predictions as to the relation between  $k_L/V$  and  $N_{Re}$  at a Reynolds number of 10,000. The dotted line represents the  $-\frac{1}{3}$  exponent of Chilton and Colburn; the sloping solid line represents the analogy developed by Sherwood on the basis of the Kármán heat-transfer analogy; and the dashed line represents the minus 0.56

exponent obtained by Gilliland from data on vaporization in a wetted-wall column with a long calming section. The four points represent the present data on cinnamic acid and beta-naphthol in 1.90- and 5.23-cm. tubes. Several other theories and analogies are omitted in order to avoid confusion.

The experimental range of values of  $N_{Re}$  covered by Gilliland was only from 0.6 to 2.5 and his empirical exponent of minus 0.56 was subject to error because the range was not wider. It will be recalled that the exponent  $- \frac{1}{3}$  employed by Chilton and Colburn was not based on diffusion data; it was chosen by analogy to a successful correlation of early data on heat transfer. In view of the uncertain basis of these two empirical relations, it appears remarkable that both are in approximate agreement with the present data in the range of  $N_{Re}$  from 1000 to 3000. Agreement of the data with the Chilton-Colburn relation is within 40 per cent. There is, of course, no experimental evidence as to what happens in the range of  $N_{Re}$  from 10 to 1000, and it is possible that the line is curved on the logarithmic graph shown.\*

If mass transfer is considered to take place solely by eddy diffusion, then the molecular diffusivity is not involved, and the Reynolds analogy should apply. If the process is controlled by molecular diffusion, through the laminar layer at the wall, then the effect of  $N_{Re}$  is evidently dependent on  $L/D$ . For very short lengths the diffusing material is accumulating in the laminar layer, and Equation (4) applies, with an indicated exponent of minus  $\frac{1}{3}$  on  $N_{Re}$  (this appears in the definition of  $j_D$ ). For relatively large values of  $L/D$  it would be expected that a steady state would have been set up in the laminar layer, with a linear solute-concentration gradient. With this situation the exponent on  $N_{Re}$  would depend on the relative importance of the two series resistances; one to molecular diffusion, and one to eddy diffusion. If  $D_L$  is very small or  $N_{Re}$  very large, the resistance of the laminar layer to molecular diffusion should be large compared with the resistance of the turbulent core, and  $k_L$  should be proportional to  $D_L$ , or to  $N_{Re}^{-1}$ . This re-

\* Hobson and Thodos (9) show that  $j_D$  involving  $N_{Re}^{-\frac{1}{3}}$  serves to correlate their data on extraction of isobutyl alcohol and of methyl-ethyl ketone by water from porous solid spheres forming a bed. The  $N_{Re}$  for these systems was 865 and 776. The indicated function of  $N_{Re}$  served to bring the data in line with the earlier data of Hougen, Ganssen, and Thodos (10), and of Hougen and Wilke (11) on vaporization of water into air using packed beds of wet porous solids. Data of Hobson and Thodos were obtained at relatively low values of  $N_{Re}$ , below the range of fully developed turbulence.

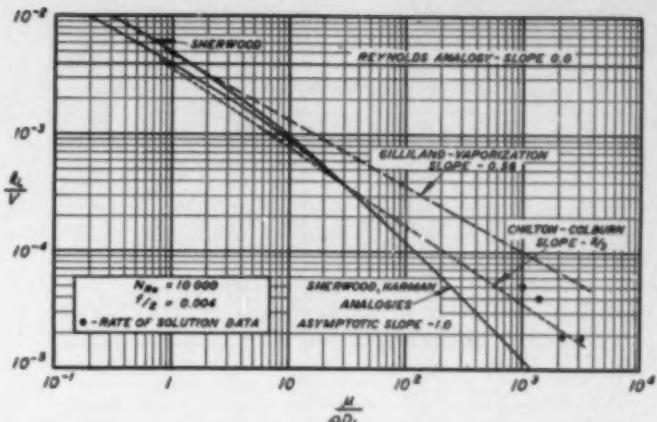


Fig. 4. Results at High Values of the Schmidt Number Compared with Various Predictions and Theories.

sult is indicated by the analogy proposed by Sherwood, as shown by the solid line having an asymptote of slope minus 1 at high values of  $N_{Re}$ .

In the light of these considerations, it is surprising that the single exponent minus  $\frac{1}{3}$  should appear to hold over a 5000-fold range of values of  $N_{Re}$ . A

TABLE I - TYPICAL DATA FOR TURBULENT FLOW IN TUBES.  
(All values tabulated are cumulative from tube inlet to L/D listed)

BENZOIC ACID			BENZOIC ACID		
Run No.: TB26B	$D = 1.90 \text{ cm.}$	$N_{Re} = 34900$	Run No.: TB25B	$D = 1.90 \text{ cm.}$	$N_{Re} = 19000$
Time : 10.0 min.	$N_{Sc} = 1870$		Time : 15.25 min.	$N_{Sc} = 1850$	
Temp. : 12.6°C.	$c_s = 2.36 \text{ g/l}$		Temp. : 14.0°C.	$c_s = 2.38 \text{ g/l}$	
$L/D$	Wt. Loss, gms.	$j_D$	$L/D$	Wt. Loss, gms.	$j_D$
7.255	0.3779	0.00785	1.145	0.2820	0.01280
5.75	1.0208	0.00778	4.19	0.9128	0.01125
9.52	1.6659	0.00771	7.42	1.5628	0.01090
15.28	2.8520	0.00779	10.96	2.2627	0.01070
17.06	2.0282	0.00780	14.56	3.0422	0.01080
20.9	3.6969	0.00776	18.2	3.8484	0.01090
24.6	4.3647	0.00778	21.85	4.6177	0.01090
CINNAMIC ACID			CINNAMIC ACID		
Run No.: TC2A	$D = 5.23 \text{ cm.}$	$N_{Re} = 25800$	Run No.: TC9A	$D = 5.23 \text{ cm.}$	$N_{Re} = 18200$
Time : 59.0 min.	$N_{Sc} = 1450$		Time : 59.0 min.	$N_{Sc} = 1450$	
Temp. : 17.8°C.	$c_s = 0.375 \text{ g/l}$		Temp. : 17.2°C.	$c_s = 0.374 \text{ g/l}$	
$L/D$	Wt. Loss, gms.	$j_D$	$L/D$	Wt. Loss, gms.	$j_D$
0.638	0.2801	0.00513	0.552	0.120	0.00651
1.78	0.4971	0.00425	1.39	0.267	0.00580
2.68	0.7860	0.00450	2.29	0.391	0.00471
			3.19	0.525	0.00464
CINNAMIC ACID			CINNAMIC ACID		
Run No.: TC29B	$D = 1.90 \text{ cm.}$	$N_{Re} = 29900$	Run No.: TC81B	$D = 1.90 \text{ cm.}$	$N_{Re} = 62000$
Time : 60.0 min.	$N_{Sc} = 2920$		Time : 60.0 min.	$N_{Sc} = 3000$	
Temp. : 6.6°C.	$c_s = 0.298 \text{ g/l}$		Temp. : 6.7°C.	$c_s = 0.296 \text{ g/l}$	
$L/D$	Wt. Loss, gms.	$j_D$	$L/D$	Wt. Loss, gms.	$j_D$
2.28	0.842	0.00275	2.75	0.2179	0.00202
5.9	0.2122	0.00268	5.85	0.4419	0.00276
9.5	0.3841	0.00262	9.05	0.6798	0.00272
15.2	0.4721	0.00267	12.4	0.9295	0.00276
17.05	0.4991	0.00266	15.9	1.2801	0.00282
20.8	0.7456	0.00268	19.5	1.5079	0.00282
24.7	0.5866	0.00268			
BETA-NAPHTHOL			BETA-NAPHTHOL		
Run No.: TN10B	$D = 1.90 \text{ cm.}$	$N_{Re} = 9170$	Run No.: TN12B	$D = 1.90 \text{ cm.}$	$N_{Re} = 17400$
Time : 100.0 min.	$N_{Sc} = 2320$		Time : 60.0 min.	$N_{Sc} = 2240$	
Temp. : 5.6°C.	$c_s = 0.280 \text{ g/l}$		Temp. : 5.5°C.	$c_s = 0.288 \text{ g/l}$	
$L/D$	Wt. Loss, gms.	$j_D$	$L/D$	Wt. Loss, gms.	$j_D$
0.787	0.0282	0.00395	1.285	0.0513	0.00387
2.75	0.0905	0.00365	3.52	0.1275	0.00351
5.38	0.1627	0.00328	5.81	0.1980	0.00352
8.46	0.2262	0.00294	8.68	0.2820	0.00315
12.3	0.3802	0.00295	11.7	0.3779	0.00318
			15.0	0.4820	0.00315

TABLE 2 - CALCULATED RESULTS FOR MASS TRANSFER INSIDE TUBES.

Run No.	$N_{Re}$	$N_{Re}$	Interpolated Values of $j_D$ at $L/D =$			
			1	2	6	20
CINNAMIC ACID - $D = 5.28$ cm.						
TC 154	280	1220	865	510	295	
TC 154	970	1570	142	117	82	
TC 54	2400	1450	131	102	68	
TC 14	2390	1000	108	82	--	
TC 144	2790	1550	101	82	--	
TC 154	4120	1500	84	70	59	
TC 124	5850	1520	74	61	50	
TC 64	7480	1410	65	52	--	
TC 114	8700	1510	67	59	56	
TC 44	10200	1410	65	58	58	
TC 104	12600	1450	59	52	49	
TC 74	14900	1420	62	58	46	
TC 84	16650	1450	56	51	45	
TC 94	18200	1450	53	48	46	
TC 84	22700	1350	54	50	47	
TC 24	35800	1450	48	45	44	
CINNAMIC ACID - $D = 5.28$ cm.						
TB 174	1140	980	146	109	67	
TB 204	1380	910	185	108	77	
TB 194	1480	910	120	90	57	
TB 184	2080	940	120	92	60	
TB 184	2820	940	104	78	52	
TB 74	3220	940	104	77	57	
TB 44	3420	900	87	68	50	
TB 104	4150	950	74	65	53	
TB 54	5110	900	78	68	47	
TB 114	6060	940	75	66	57	
TB 24	7100	950	71	59	52	
TB 64	8600	1000	79	64	52	
TB 18	11800	950	60	52	46	
TB 154	12200	1110	65	57	52	
TB 84	15500	1050	70	60	62	
TB 144	16100	1110	58	52	49	
TB 124	20700	1100	52	47	46	
TB 74	22200	1000	44	45	52	
TB 94	26200	1040	57	54	58	
TB 124	26500	1090	51	46	45	
TB 224	38400	1240	48	45	46	
CINNAMIC ACID - $D = 1.90$ cm.						
TC 178	910	2520	129	98	67	
TC 188	1220	2700	119	97		
TC 208	2440	2880	88	78	75	
TC 118	8420	2940	78	70	68	
TC 228	5160	2950	62	58	56	
TC 288	6780	2850	55	47	45	
TC 248	9560	3110	56	53	51	
TC 248	11200	2550	29	46	35	
TC 258	12910	2880	48	40	40	
TC 278	13150	2810	37	37	37	
TC 258	18000	2750	35	33	32	
TC 288	21200	2840	30	20	20	
TC 848	28200	3200	31	29	20	
TC 298	29900	2920	28	26	26	
TC 328	31200	2280	29	29	29	
TC 368	40200	3200	29	28	28	
TC 208	50000	2880	35	32	31	
TC 818	62000	3000	29	28	28	
TC 578	65200	3080	34	29	27	
TC 328	68400	3160	28	27	26	
BETA-BAPTHOL - $D = 1.90$ cm.						
TB 58	1400	2170	112	87	65	
TB 68	1940	2170	75	60	48	
TB 78	2820	2810	69	68	57	
TB 68	4480	1740	52	41	24	
TB 98	6480	2180	28	25	24	
TB 108	9170	2850	35	22	29	
TB 28	11700	2110	35	21	20	
TB 118	15400	2070	28	22	21	
TB 28	17400	2840	26	21	20	
TB 28	22400	2940	29	23	29	
TB 18	25100	2440	26	28	28	
TB 128	46700	2460	23	26	24	
BENZOIC ACID - $D = 1.90$ cm.						
TB 428	980	2100	152	112	80	
TB 428	1280	2120	114	87	68	
TB 448	1750	2220	90	69	50	
TB 458	2450	2260	89	71	60	
TB 468	2580	2250	91	82	81	
TB 478	4920	2240	95	106	110	
TB 488	6880	2290	128	129	148	
TB 348	8210	2280	121	122	122	
TB 408	9900	2240	112	116	117	
TB 558	12000	2250	84	88	92	
TB 418	14000	2420	88	79	79	
TB 498	14500	3220	105	106	98	
TB 528	16400	2160	115	115	115	
TB 748	17700	1970	85	77	78	
TB 758	19000	1850	118	110	109	
TB 248	28400	2800	90	81	81	
TB 278	84000	2270	75	74	70	
TB 248	84900	1870	74	78	78	
TB 288	46200	2350	85	69	62	
TB 298	64500	2420	80	66	63	

possible explanation has been suggested by Lin (16), who points out that by analogy to the observed boundary-layer oscillation resulting from free stream turbulence one would expect disturbances in the transition zone between turbulent and laminar layers to propagate sidewise into the laminar layer. The resulting motion normal to the pipe wall would be expected to increase mass transfer in this region. For  $N_{Re} = 1000$  the momentum diffusivity ( $\mu/\rho$ ) is 1000 times the mass diffusivity ( $D_L$ ), and mass transfer might be expected to be 1000 times as sensitive to disturbances. At the other end of the scale, for  $N_{Re}$  less than 1, momentum transfer should be the more sensitive, and analogies to friction should predict high values of  $k_L$  (this effect is indicated by the results of Martinelli for heat transfer at very low values of the Prandtl group). In effect, Lin suggests that the laminar film behaves slightly turbulent.

If this suggestion is sound, the data should fall high, as they do on Figure 4. In another sense it may be said that the Sherwood analogy or its equivalent is sound but that the effective  $D_L$  is increased, and that  $N_{Re}$  is really smaller than calculated from molecular diffusivities. Pending further development of this concept, the Chilton-Colburn analogy may be taken as providing a good correlation of the existing experimental data over a wide range of values of  $N_{Re}$ .

**Solution of Flat Plates.** Data on solution of flat cast plates of benzoic and cinnamic acids are shown in Figure 5. Since the thin plates used had a width equal to the diameter of the 5.23-cm. test section, the results cannot be taken as representative of transfer from a plane surface to a large body of water. For this reason they have only semi-quantitative value. It may be noted that the points fall 20 to 100 per cent above the Chilton-Colburn line, agreeing better at low values of  $N_{Re}$ . Since  $N_{Re}$  was 1000 or more, slight changes of the  $2/3$  exponent on  $N_{Re}$  in  $j_D$  would make the agreement better or much worse, and it is perhaps remarkable that the data check the Chilton-Colburn line as well as they do.

As in the case of the tubes, the points for benzoic acid are high. It is significant that the three benzoic acid points which fall in with those for cinnamic acid are for tests in which the plates had been sanded smooth after casting.

**Single Cylinders.** Figure 6 shows the data obtained on the solution of cast cylinders of benzoic and cinnamic acids. The cinnamic acid data fall slightly below the Chilton-Colburn line; the benzoic acid data again are higher, checking closely the recent experimental data of Maisel and Sherwood on vaporiza-

tion of liquids from wet cylinders placed in turbulent streams of air and other gases. Since  $N_{de}$  was similar for both solutes, no change in the  $\frac{1}{3}$  exponent can bring the two sets of data together. Even with this discrepancy, the new data check the Chilton-Colburn line as well as do the experimental data on vaporization.

**Spheres.** Figure 7 shows the data on benzoic acid spheres, which are seen to check well with the recent data of Maisel and Sherwood on vaporization from single wet spheres in air. This is similar to the agreement noted for cylinders. The solid line represents the general correlation obtained by Williams (22) from a study of the large amount of data in the literature on vaporization from drops and wet spheres. Somewhat better agreement of the data with Williams' line would be obtained if the velocity of the water at the axis of the test section were used in place of the average velocity in the test conduit in which the spheres were placed.

Points shown at the upper left were reported by McCune and Wilhelm (18) for the solution of beta-naphthol pellets resting on a wire screen.

#### Acknowledgment

The material presented was taken from the Sc.D. Thesis of W. H. Linton, Jr. The data on single cylinders and spheres were obtained as part of an associated S.M. thesis by R. P. Gates and R. Shanks (7). The data on flat plates were obtained by H. E. Battey (2) as part of a thesis for a bachelor's degree.

#### Notation

$c$  = concentration of exit stream, g./cu.cm.

$c_0$  = concentration of inlet stream, g./cu.cm.

$c_s$  = concentration at saturation, g./cu.cm.

$C$  = specific heat, g.cal./(g.) ( $^{\circ}$  C.)

$D$  = diameter, cm.

$D_L$  = molecular diffusivity, sq.cm./sec.

$e$  = surface roughness, cm.

$f$  = friction factor, dimensionless

$G$  = mass velocity, g./ (sec.) (sq. cm.)

$h$  = individual heat-transfer coefficient, g.cal./ (sec.) (sq.cm.) ( $^{\circ}$  C.)

$$j_B = \frac{k_L}{D} \left( \frac{\mu}{\rho D_L} \right)^{\frac{1}{3}}$$

$$j_H = \frac{h}{CG} \left( \frac{C\mu}{k} \right)^{\frac{1}{3}}$$

$k$  = thermal conductivity, g.cal./ (sec.) (sq.cm.) ( $^{\circ}$  C./cm.)

$k_t$  = mass-transfer coefficient, g.

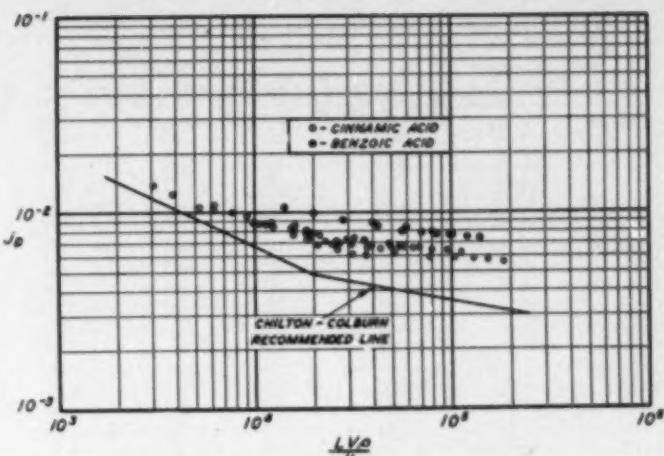


Fig. 5. Data on Rates of Solution of Flat Plates.

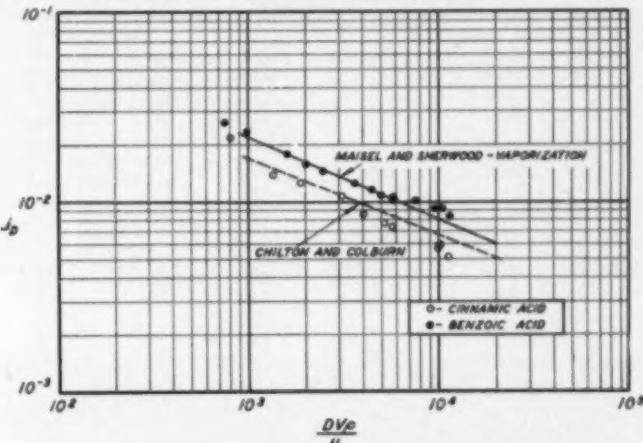


Fig. 6. Data on Rates of Solution of Transverse Cylinders.

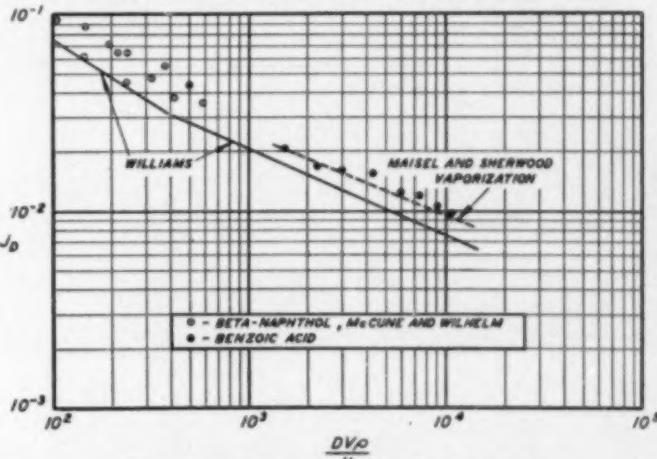


Fig. 7. Data on Rates of Solution of Solid Spheres.

TABLE 3 - MASS TRANSFER INSIDE TUBES - STREAMLINE FLOW NINE.

Run No.	Cum. L/D	Cum. Wt. Loss, gm.	$10^3 j_D$	$10^{-3} W/D_L \mu L$	$10^6 c/c_0$
HEPTANOIC ACID - D = 1.90 cm.					
TD 42B	0.619	0.0500	2180	2490	821
	8.82	0.1885	1800	405	1210
	7.20	0.2987	1095	214	1919
	10.71	0.3958	972	145	2510
	14.21	0.4819	895	108	3090
	17.85	0.5495	840	86.2	2650
	21.40	0.6473	798	71.9	4160
	25.10	0.7228	760	61.8	4650
TD 43B	0.619	0.0403	1370	8450	284
	2.82	0.2867	1000	558	921
	7.20	0.3772	844	296	1465
	10.71	0.5014	755	199	1950
	14.21	0.5131	695	150	2020
	17.85	0.7244	645	119	2820
	21.40	0.8577	680	95.5	2740
	25.10	0.9467	610	85	3750
TD 44B	0.692	0.0517	978	8420	205
	2.02	0.1068	880	1310	428
	8.52	0.1701	816	866	671
	6.17	0.2598	700	495	1010
	9.76	0.3541	612	312	1410
	13.3	0.4409	560	229	1740
	16.95	0.5277	526	180	2080
	20.5	0.6108	509	149	2410
	24.1	0.6984	485	127	2780
	27.7	0.7700	470	110	2840
CINNAMIC ACID - D = 1.90 cm.					
TC 17B	0.682	0.0207	1990	2640	289
	2.95	0.0510	1120	604	714
	6.59	0.1014	990	278	1420
	10.25	0.1255	800	176	1760
	14.0	0.1708	799	129	2890
	17.84	0.1921	704	101	2680
TC 18B	2.75	0.0525	1120	944	625
	5.85	0.1009	1010	444	1200
	9.05	0.1859	880	277	1620
	12.4	0.1776	836	209	2120
	15.9	0.1973	728	168	2860
	19.5	0.2858	707	135	2800
HEPTANOIC ACID - D = 1.90 cm.					
TD 5B	1.81	0.0678	1145	1820	488
	4.59	0.1881	920	520	994
	8.84	0.2224	819	287	1470
	12.15	0.2963	745	197	2180
TD 6B	1.94	0.0477	768	1700	348
	4.57	0.0945	640	721	687
	8.88	0.1491	558	894	1090
HEPTANOIC ACID - D = 5.22 cm.					
TD 16A	1.22	0.598	1120	1260	572
	2.44	0.912	865	680	880
	2.60	1.282	790	426	1190
	4.82	1.428	688	319	1280
	6.0	1.615	621	256	1560
TD 17A	0.95	0.283	1580	876	612
	2.18	0.419	1010	391	905
	3.34	0.562	864	249	1210
	4.44	0.664	767	187	1440
	5.85	0.744	718	156	1610
	6.28	0.829	685	182	1810
TD 19A	1.21	0.483	1120	962	595
	2.39	0.691	840	487	850
	2.61	0.881	707	222	1085
	4.82	1.036	625	241	1275
	5.92	1.186	580	197	1460
TD 20A	1.22	1.559	1285	780	658
	2.44	2.487	1025	390	1046
	2.60	3.751	905	264	1880
	4.82	3.988	828	197	1690
	6.0	4.689	786	158	1990
CINNAMIC ACID - D = 5.22 cm.					
TC 15A	0.552	0.0546	8720	440	664
	1.16	0.1094	8540	209	1320
	1.79	0.1590	8340	135	1920
	2.69	0.2800	8280	90.5	2800
	3.59	0.3252	8500	67.5	4050
TC 16A	0.552	0.0678	1740	2160	280
	1.18	0.1129	1360	1010	468
	2.08	0.1652	1180	572	686
	2.87	0.2084	1010	415	846
	3.78	0.2494	930	311	1025
	4.55	0.2883	900	262	1195
	5.50	0.3329	860	216	1280

mole/(sec.) (sq. cm.) (g.  
mole)/(cu.cm.)

L = length, cm.

N<sub>Pr</sub> = Prandtl group, C<sub>P</sub>/k

N<sub>Re</sub> = Reynolds number,  $\frac{LV\rho}{\mu}$ , or  
 $\frac{L V \rho}{\mu}$

N<sub>Sc</sub> = Schmidt group,  $\mu/\rho D_L$

V = velocity, cm./sec.

W = flow rate, g./sec.

x = distance in direction of flow,  
cm.

y = distance from wall, cm.

$\rho$  = density, g./cu.cm.

$\mu$  = viscosity, g. / (sec.) (cm.)

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(Presented at Forty-second Annual Meeting, Pittsburgh, Pa.)

# • NEWS SECTION •

## MOBILE LABORATORY IN PENNSYLVANIA

A new air pollution and industrial hygiene mobile laboratory has been placed in service by Pennsylvania's Bureau of Industrial Hygiene. The mobile laboratory will be used by the Pennsylvania Health Department's new air pollution division to investigate smog conditions and other atmospheric contamination throughout the state's industrial areas.

Designed and supplied to the state by Mine Safety Appliances Co., Pittsburgh, the laboratory is equipped with more than 25 scientific devices for field sampling and quantitative and qualitative analyses of atmosphere in industrial communities and factories.

One of the laboratory's principal devices is an electrostatic sampler for the detection of all types of particulates, including dust, fumes and smoke resulting from many industrial processes. Operating on the principle of electrical precipitation, this sampler has a portable head which contains an ionizing electrode, a collecting tube and motor-blower assembly that provides for a flow of 3 cu.ft./min. Particles present in the incoming air are charged by the electrons and are deposited on the collecting tube. Determinations then can be made by weight without removing the sample from the tube, or further tests can be undertaken by extracting the samples. The laboratory is in a closed route van-type body with specially designed built-in work benches, cabinets, racks, and storage compartments.

According to Governor Duff the laboratory will play an important part in the state's effort to keep the atmosphere in industrial committees free from hazardous or annoying fumes, dusts and gases.

## MONSANTO TO UP PHOSPHORUS OUTPUT

Plans to construct a sixth electric furnace at the Monsanto (Tenn.) plant of the Monsanto Chemical Co. for the production of elemental phosphorus were announced in April.

The new furnace, which will have a capacity of 25,000 kw., will be the largest phosphorus furnace in the world and one of the largest electric furnaces ever built.

J. L. Christian of St. Louis, general manager of Monsanto's phosphate division, stated that the new furnace is being constructed "to bring about a sizable increase in the production of phosphorus." The fifth furnace was completed at this location in October, 1948. The new furnace is expected to be completed during January, 1951.

Additional expansion of the phosphate division's plant at Trenton, Mich., also was announced. The facilities there for the production of sodium and ammonium phosphates will be expanded. Facilities at the division's Carondelet (Mo.) plant for the production of calcium phosphates also will be enlarged.

## SYNTHETIC BENZENE FOR PAN AMERICAN

Successful commercial production of synthetic benzene from petroleum at Pan American's Texas City refinery, was revealed last month as a product of company's chemical division, by L. W. Moore, president of Pan American Refining Corp., and F. J. Smith, manager

of Pan American chemicals division.

The first trial run on plant equipment took place in April, 1949, and full commercial production started in December. Mr. Moore emphasized that the benzene is a synthetic material and is not obtained by recovery from normal refinery streams. It is made by the dehydrogenation of cyclohexane and the isomerization and dehydrogenation of methyl cyclopentane. Existing facilities at the Texas City plant are estimated to be capable of the manufacture of between three and five million gallons of benzene a year.

Benzene is in short supply at present, owing to coke plant shutdowns and expanding markets. The successful commercial synthesis by Pan American provides a new source of supply.

## GOODYEAR TO EXPAND VINYL OUTPUT

An expansion program to quadruple the output of vinyl resins for the plastics industry, was announced by The Goodyear Tire & Rubber Co.

## MOBILE LABORATORY JUST PLACED IN SERVICE



Pennsylvania's mobile laboratory contains all types of instruments to collect, detect and identify air contaminants, explosive gases and other hazards. Shown here as the laboratory was turned over to the state during a presentation ceremony at the capitol in Harrisburg are (left to right) Pennsylvania's Governor James H. Duff; Mine Safety Appliances Co.'s President George H. Deike, Sr.; State Health Department Secretary Dr. Norris W. Vaux, and State Industrial Hygiene Bureau Director Dr. Joseph Shilen.

P. W. Litchfield, Goodyear chairman of the board, said the expansion will be made at the company's chemical division subsidiary, the Pathfinder Chemical Corp. at Niagara Falls, N. Y., at a cost of \$2,250,000.

Potential production figures were not released. The expanded program will make the Goodyear organization one of the leading producers of vinyl resins.

#### A.E.C. AIR FILTER FOR INDUSTRY

A new paper-like filter material designed for filtering fine radioactive particles from contaminated gaseous wastes has been developed for the Atomic Energy Commission and may have general commercial or industrial use in filtering smokestack gases according to the developing group, Arthur D. Little, Inc.

The new material contains treated paper-making fibers in combination with finely divided mineral asbestos fibers. The material is made in soft, flexible sheets which can be pleated and formed into shapes to fit filtering units of large capacity.

AEC facilities using cooling or ventilating air which might become contaminated with radioactive particles take extreme care to eliminate such particles before the air is discharged into the atmosphere. Air filters developed and used by the Chemical Warfare Service for protection against gas warfare have proved satisfactory, and for some years the Army has been supplying AEC with filter units. With the expansion of the atomic energy program, however, the demand for filters has grown rapidly. In order to develop alternate sources of supply and possibly to reduce filter costs, the AEC initiated a program for filter research and development.

The material was developed by Arthur D. Little, Inc., under contract with AEC.

The filter units consist of deep, closely spaced pleats of filter paper fitted into wooden frames. The pleats are spaced and kept in line by deformed separators of ordinary paper which hold them in place and permit easy passage of the air to be filtered. The paper pleats and separators are anchored into wooden frames with plastic adhesives. The frames are in turn glued and screwed at all corner joints to produce a perfectly tight assembly. Gaskets of soft sponge rubber cemented around the edges of the frames prevent air leaks when the frames are clamped into place.

#### INSTRUMENT COURSE OF FISCHER & PORTER

The third quarterly instrumentation course for 1950 at the Hatboro (Pa.) plant of the Fischer & Porter Co. will

begin on July 10.

Manufacture, calibration, installation, operation and maintenance of flow (variable-area and orifice), liquid level, specific gravity and viscosity instruments will be covered, according to the company.

#### MATHIESON HYDRO-CARBON CORP. FORMED

Thomas S. Nichols, president of Mathieson Chemical Corp., Baltimore, Md., revealed last month that plans for the organization of Mathieson Hydro-carbon Chemical Corp. were completed.

The new company, a \$27,000,000 joint venture of Mathieson Chemical Corp. and the shareholders of Tennessee Gas Transmission Co., will produce chemicals from natural gas transported by Tennessee over its pipeline network from Texas and Louisiana fields to the northern and eastern markets.

More than 2,000 acres of land have been acquired by the new company near Brandenburg, Ky., southwest of Louisville on the Ohio River, and chemical units costing \$17,000,000 to be constructed at that point will be completed at the end of 1951. The company will also build a \$6,000,000 plant for the production of raw material components at another location.

Mr. Gardiner Symonds, president of Tennessee Gas Transmission Co., said his company was building a \$12,000,000 stripping plant near Greensburg, Ky., to separate hydrocarbons from natural gas. A pipeline will be constructed to bring them to the new hydrocarbon chemical plants.

A major portion of the initial output of the new company has already been contracted for, according to this announcement.

In commenting on the new company, Mr. Nichols said:

This development marks the entry of Mathieson Chemical Corporation into the important and growing field of petrochemicals.

The decision to build the plant on Tennessee's pipeline in Kentucky assures the company of a large volume of low-cost raw materials for a long term, and at a point close to the principal markets for the chemicals it will produce.

Officers of the new company have been elected as follows: Thomas S. Nichols, president (president of Mathieson); John C. Leppart, executive vice-president (executive vice-president of Mathieson); Russell Hopkinson, administrative vice-president; Carl F. Prutton, vice-president, operations (vice-president-director of operations, Mathieson); S. deJ. Osborne, treasurer and secretary (vice-president-treasurer, Mathieson).

#### LITTLE A.E.C. TECHNOLOGY WITHHELD

Technological information uncovered in atomic energy research and of potential interest to American industry is being declassified on a fairly satisfactory basis according to the preliminary conclusions of a technological working party which has been searching the abstract file maintained by the Patent Branch of the Atomic Energy Commission.

Members of the working party, representing technical and engineering societies and the business press, were given complete security investigation and clearance to enable them to enter restricted areas and to examine restricted information files.

Following its work with the patent abstract files, the working party has expressed willingness to continue work on the AEC's trial program to make atomic energy information more readily available to industry.

To accomplish this the AEC has authorized an expansion of the scope of the test program to include a study of the technology of electromagnetic separation which has been carried on primarily at the Y-12 installation at Oak Ridge, Tenn. This is not immediately and directly related to the present weapons operations in the national atomic energy program.

The working party will have an opportunity to evaluate technology developed in connection with the electromagnetic separation process, with the exception of production data bearing on capacities and enrichments in the process.

Members of the group will scrutinize applicable individual technical reports on processing and operations of the Y-12 plant; inspect the electromagnetic separation plant operations; and examine plant technology with the aid of engineering and technical personnel.

In searching the patent abstracts members of the working party reviewed a sample of approximately 800 abstract files. On the basis of this examination the group concluded:

1. That the declassification of technological information through the normal declassification routine is proceeding fairly satisfactorily, but that some classified patent applications of industrial interest should be submitted for declassification.
2. That there appears to be in the fields specified for study by the working group in the files of the Patent Branch, no great store of unclassified or clearly declassifiable technological information which has not been declassified and which would be of great usefulness to American industry.
3. That further review of the classified files of the Patent Branch by the

(Continued on page 25)

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For many years "the only completely satisfactory answer to many corrosion and contamination problems," genuine Lapp Chemical Porcelain is now available in a series of valves completely armored in acid-resisting heat-treated silicon aluminum. Choose the Lapp armored porcelain valve over expensive alloy or lined valves for greater economy—chemical stability—plant, and personnel protection against carelessness or accident. Standard bolt bonnets integral with armor. Y-valves in 1", 1½", 2", 3", 4" and 6" sizes; angle valves in 1" and 2" sizes; flush valves in 1½" and 3" sizes (for tank outlets 2", 4" and 5"). Write for descriptive literature and specifications. Lapp Industrial Co., Inc., Process Equipment Division, 213 Maple St., LeRoy, N.Y.

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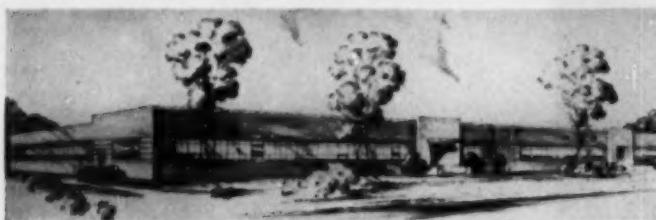
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## B. F. GOODRICH'S RESEARCH LABORATORY AT AVON LAKE



Architect's drawing of the new applied research laboratory to be built at Avon Lake, Ohio, for the B. F. Goodrich Chemical Co. The new laboratory will be the third unit in the company's multimillion dollar installation near Cleveland. A general chemicals plant and a semiworks plant have been completed and are in operation.

The new one-story building will cover 17,500 sq. ft. and will have separate materials and processing laboratories, a compounding room, Banbury mixing room, controlled temperature testroom, offices and conference rooms. The technical staff will have an efficient testing apparatus for conducting general evaluation studies on thousands of products and materials, and other facilities with which to carry out the task of developing processing techniques, and offering to customers technical assistance on their problems.

## CORNING GLASS BUILDS NEW PILOT PLANT

Construction has started in Corning, N. Y., on a new pilot plant for Corning Glass Works, it was announced recently by The H. K. Ferguson Co., industrial engineers and builders. Of steel-frame and brick construction, the two-story plant will contain 51,000 sq. ft. and will be three times as large as the pilot plant which the company put into operation in 1946. The 1946 pilot plant will continue to work on laboratory and experimental projects.

The pilot plant will be used to develop manufacturing processes from basic findings. Initial efforts will be concentrated on improving television bulbs, the glass enclosures for television tubes.

The new structure will be a complete manufacturing unit designed to test experimental production methods on a factory scale. A 60-ton glass melting tank will be housed in a separate structure at the rear of the plant.

## NEW ENGLAND IND. WASTE CONFERENCE

A three-day New England Industrial Wastes Conference to be held June 26-28, will be a feature of the 1950 Summer Session at the Massachusetts Institute of Technology. The MIT department of civil and sanitary engineering will be joined in sponsoring the event by the New England Council and the New England Sewage Works Association.

Prof. Walter H. Gale, director of MIT Summer Session described the conference as part of a broad series of

summer activities scheduled during 1950 to make the Institute's special facilities available to those in industry and technology who cannot participate in its regular program. In addition to general discussions of pollution abatement from the viewpoints of industry, control agencies and municipalities, there will be symposia on water and waste problems of specific New England industries, including pulp and paper.

## FILM CHEMISTRY AWARD AT SPEED SCIENTIFIC

The chemical engineering department of the Speed Scientific School of the University of Louisville has announced an award of \$1,500 to continue the Federation of Paint and Varnish Production Clubs' Fellowship in an investigation of "The Chemistry of Film Formation, Film Properties, and Film Deterioration." This research is an international undertaking sponsored by the Federation and carried on a cooperative basis by interested groups around the world.

The entire project is under the general supervision of Dr. W. O. Lundberg, who is charged with correlation of the various groups. The project at the Speed Scientific School is under the supervision of Dr. Gordon C. Williams, head of the chemical engineering department.

The chemical engineering department of the University of Louisville has been studying three phases of the project: the change in chemical composition of the aging film, the change in polymerization of the aging films, and the adsorptive properties of the polymeric residues of solvent extracted films.

## DEADLINE ENGINEERING SURVEY EXTENDED

The closing date of the nationwide survey of selected engineering personnel sponsored by the Engineers Joint Council for the U. S. Office of Naval Research, has been advanced to July 15, 1950. The originally scheduled closing date was March 15. Up to date, however, only two-thirds of the 115,000 questionnaires which were sent out, have been returned by the engineers. The survey is intended to serve as a file of key engineers working in research, development and other scientific projects who can be called in on a full- or part-time basis to work on the scientific programs of the National Military Establishment. Even though an engineer may not now be engaged in research or development work, his services may be important to the country by virtue of his special training and professional recognition granted him by his professional society.

The questionnaires were mailed to engineers holding the full professional grade of membership in 18 national engineering societies. Since a third of the forms is still missing and especially since the omission of so large a segment of the engineering profession from the proposed file will limit its usefulness, the Office of Naval Research has authorized the mailing of a third reminder to delinquent engineers.

The questionnaires are being processed by the American Society of Mechanical Engineers, contracting agent under an ONR agreement. The survey is managed by the EJC committee.

## NATIONAL CONFERENCE ON IND. HYDRAULICS

The sixth annual National Conference on Industrial Hydraulics will be held Oct. 18-19 at the Sherman Hotel in Chicago, it was announced recently by conference director Otto J. Maha, president of the Hannifan Corp., Chicago.

Sponsors of the nonprofit, noncommercial technical conference are Armour Research Foundation of Illinois Institute of Technology and the Graduate School of the Institute, with the cooperation of the following technical societies: American Society of Civil Engineers, American Society of Mechanical Engineers, Society of Automotive Engineers, Western Society of Engineers, American Society of Lubricating Engineers, American Institute of Chemical Engineers, and the Institute of Aeronautical Sciences.

Frank W. Edwards, director of civil engineering at Illinois Tech, is conference secretary.

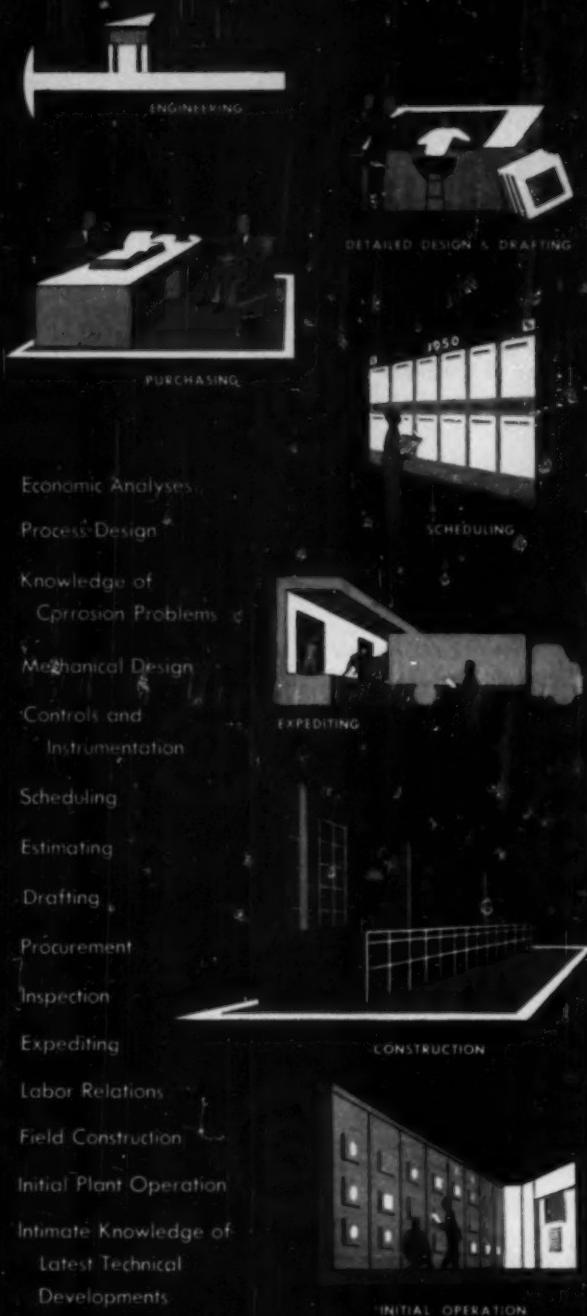
(More Industrial News on page 17)

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# Problem-Corroded, plugged-up,

## Solution-BS&B SAFETY HEADS!

**BS&B SAFETY HEADS** are the answer to your relief valve problem. These precision devices give extra protection to relief valve operation. They can be used: (1) Under your existing relief valve (2) As secondary relief devices (3) As sole pressure relief devices (4) At outlet of certain types of relief valves.

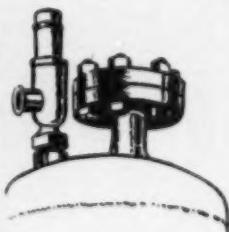
### 1. Under your existing relief valve

A SAFETY HEAD under your relief valve isolates the valve from vessel contents. Leakage through the valve is halted until the SAFETY HEAD rupture disc is burst by over-pressure. For this use a bleed line must be installed in the chamber between the valve plug and the rupture disc, enabling the operator to determine if rupture disc is intact.



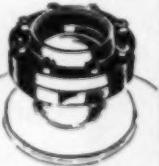
### 2. As a secondary relief device

. . . when operation is close to the relief valve setting. As a secondary relief device, the rupture disc can be rated much higher than the valve setting. If the valve fails to function or capacity inadequate you are certain of positive protection when pressure rises to the predetermined bursting pressure of the disc.



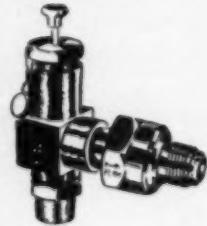
### 3. As sole pressure relief device

This installation is used when it is not necessary to have a shutoff or when materials handled are not toxic or flammable.



### 4. At outlet of certain types of relief valves

A SAFETY HEAD at the relief valve outlet will stop leakage until pressure builds up to the designed bursting pressure of the rupture disc. In this use the valve design must not permit an increased pressure setting of the valve due to pressure in the chamber between the rupture disc and the valve plug. Not recommended where corrosive or viscous materials might contaminate internal parts of the valve.



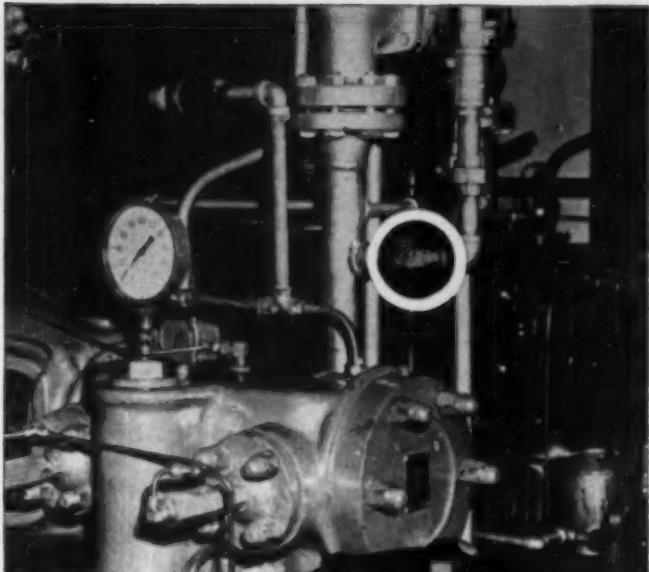
### Now—New Catalog!

It's now being prepared...the new BS&B SAFETY HEAD catalog. Gives you all the facts...all the answers to your questions about these amazing safety devices. Reserve your copy now by mailing the coupon on opposite page!

### FREE ANALYSIS!

Jim Myers, SAFETY HEAD Sales Manager will have a BS&B engineer analyse your pressure relief problems and submit suggestions to you WITHOUT COST OR OBLIGATION. Mail the coupon on opposite page or call GRand 6700, Kansas City, Mo. Do it now!

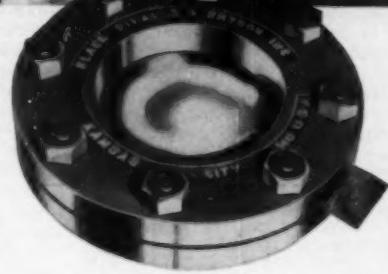
# leaky relief valves...



A typical BS&B SAFETY HEAD installation is shown above. The white circle surrounds a 600# Union type Safety Head with a Monel metal, rupture disc rated 400# bursting pressure at 150 degrees F (275# operating pressure) installed on an Ingersoll-Rand two-stage hydrogen compressor.

The pre-determined bursting pressure is established with a safe margin above operating pressure. Correct element resistant metals are used in fabrication of the rupture discs.

BS&B SAFETY HEADS are rapidly becoming standard installations on compressed gas and air equipment. Once the complete BS&B SAFETY HEAD story is understood... for un-telling protection to both property and the lives of personnel... there is little delay in order placing. Investigate BS&B SAFETY HEADS at once.



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## TRAINING FOR SALES ENGINEERS

A new training program for sales engineers will start June 19 at the Evening and Extension Division of The City College of New York School of Business. Developed in close collaboration with an advisory board of nine industrial leaders, the Salesmanship for Engineers program will total 300 hours of instruction and will be completed in 15 weeks of daytime or 25 weeks of evening training.

According to Dr. R. A. Love of the school the program will be open only to men with a technical background. They will be given no further engineering instruction but will get practical training in selling skills and marketing procedure. Classes will be conducted by sales training specialists who are conversant with engineering.

One-half of the course will be devoted to techniques of salesmanship, including such selling skills as the approach, the demonstration, meeting objections, and handling the interview. The largest portion of the remainder, 60 hours, is given over to practicing speech in selling. Thirty hours will be spent in a survey of industrial marketing, while the last 60 hours are evenly divided among market analysis, advertising, and marketing problems as they affect the industrial salesman.

Further information about the new course may be obtained by writing to Supervisor of Admissions, City College Midtown Business Center, 430 West 50th Street, New York 19, N. Y.

## ROCKEFELLER GIVES

M.I.T. \$1,000,000

A gift of \$1,000,000 to the Massachusetts Institute of Technology by John D. Rockefeller, Jr., was announced during the month by Marshall B. Dalton, chairman of the M.I.T. development program.

Addressing the third meeting of more than 200 alumni members of the National Committee on Financing Development, which was established in 1948 to "fund M.I.T.'s independence" through the current \$20,000,000 Development Program, Mr. Dalton reported that including the Rockefeller gift, the total to date is \$12,162,309.15.

In making the gift to M.I.T., Mr. Rockefeller wrote Dr. James R. Killian, Jr., president of the Institute, that "Without in any way desiring to restrict the use of this gift, may I say that the part of the development program which provides for continuing operating needs appeals especially to me in that it is directed toward the buttressing of the Institute's financial stability and independence as a private institution."

**BS&B**  
**SAFETY**  
**HEADS**

# MARGINAL NOTES

News of Books of Interest to Chemical Engineers

## Good Chemical Engineering Tool

**Introduction to Chemical Engineering Thermodynamics.** J. M. Smith. McGraw-Hill Book Co., New York. (1949) 386 pp. \$4.00.

Reviewed by *Bernard W. Gamson, Chief Process Engineer, Great Lakes Carbon Corp., Chicago, Ill.*

PROFESSOR Smith has written an introductory text on thermodynamics from a chemical engineering viewpoint. It covers an elementary treatment of the first and second laws of thermodynamics, coupled with sections on the thermodynamic behavior of fluids, application of thermodynamics to problems in the compression and expansion processes, flow of fluids, refrigeration, phase equilibria and chemical reaction equilibria.

Treatment of the first law employs use of differential symbols for  $Q$  and  $W$  for the differential change in internal energy. Although the author indicates that these are not exact differentials, use of such nomenclature is likely to be misleading and confusing to the beginner, especially when such usage is extended to the second law in the definition and calculation of entropy. This technique of mathematical symbolism leaves the reader with the impression that his Equation (5-44) which relates the differential internal energy in terms of pressure, volume, temperature and entropy as being valid for only a reversible process.

Although this is an introductory text, it would be desirable to include a more comprehensive treatment of the thermodynamic properties of gaseous and liquid mixtures and single-phase properties of liquids in the vicinity of the critical point. The section on chemical reaction equilibria would be more complete if consideration were given to equilibria occurring under electrical forces. This is desirable in view of the growth of the electrochemical industries.

This book is well written and for chemical engineering students should prove a valuable introduction to the study of thermodynamics, especially when used as a chemical engineering tool. Generalized methods for calculating thermodynamic properties of fluids are introduced early in the text. It is copiously illustrated with numerical examples, and thermodynamic concepts

are explained in words as well as equations. To the beginner, this method of presentation should be particularly appealing. This text will be useful in undergraduate courses in chemical engineering.

## New Improved Edition

**Standards of Tubular Exchanger Manufacturers Association (Second Edition).** Tubular Exchanger Manufacturers Association, 53 Park Place, New York 7, N. Y. (1949) 93 pp. \$3.00.

Reviewed by *Donald L. Katz, University of Michigan, Ann Arbor, Mich.*

THIS booklet of TEMA Standards was compiled by the technical committee of the Association, Thomas H. Miley, chairman, and Townsend Tinker, editor. It sets forth the recommended standards for the mechanical and thermal design and construction of cylindrical shell and bare tube heat exchangers. The second edition is a revision and enlargement of the first edition published in 1941.

The Standards are reorganized and are coded with a letter and number for each paragraph, chart, and table. Most sections of the second edition are considerably expanded from the first edition. Much of the enlargement is concerned with the mechanical design, with the following notable additions:

- a. Standard tolerances for external dimensions, nozzles, tube sheets, baffles, covers, and flanges.
- b. Table of baffle or support plate thicknesses.
- c. Standards for channels and channel covers.
- d. Hub flanges for 75- and 600-lb. standards in addition to 150, 300, and 450 lb.
- e. Ring flanges for 75, 150, and 300 lb.

In the section on thermal standards, old graphs have been redrawn to make them more readable and new graphs of viscosity, thermal conductivity, and specific heat are included. Charts giving friction factors and heat-transfer characteristics for flow across staggered tubes with equilateral triangular pitch are notable additions. Fouling factors are reorganized but otherwise the same as in the first edition.

The second edition is a distinct improvement over the first edition, with respect to content and workmanship.

## Especially for Teachers

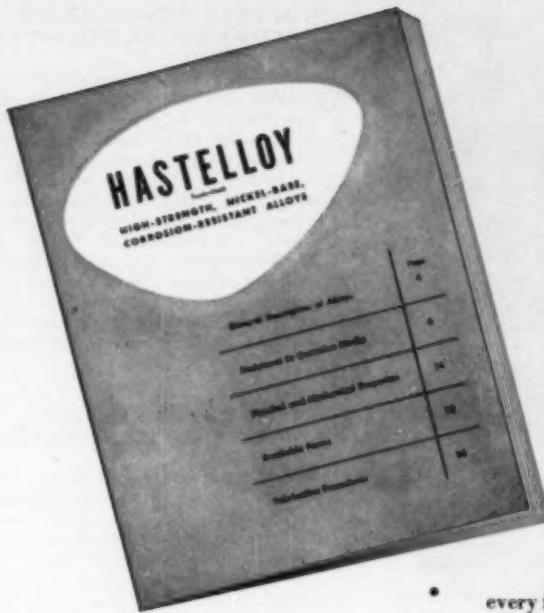
**Transactions of the Chemical Engineering Division, American Society for Engineering Education.** Third Summer Session for Chemical Engineering Teachers (1948). Chemical Engineering Department, Bucknell University, 432 pp. \$2.00.

Reviewed by *Albert B. Newman, Chemical Engineering Department, College of City of New York.*

THIS book is an assembly of mimeographed papers furnished by the speakers at the summer session held at the University of Wisconsin in 1948. All told, there are 41 papers by teachers and engineers in industry. Many of these papers deserve special comment, but this review will mention specifically only one paper: the one on the Progress in Unit Operations, by Thomas H. Chilton. Here, with a splendid bibliography, is assembled concisely the pertinent information about unit operations aspects of the atomic bomb and other wartime projects, besides the advances in the more well-known operations. The fact that there are only four papers on unit operations points up the fact that this field is becoming standardized educationally. There are five papers each on thermodynamics and chemical reaction kinetics, indicating increasing educational interest in the development of these subjects. It is surprising to find as many as seven papers on unit processes, a concept that many chemical engineers consider illogical. Laboratory instruction comes in for five papers. The remaining papers are on report writing, electrochemistry, mathematics, instrumentation, the graduate program, teacher qualifications and development, and plastics technology.

For anyone in the teaching end of the chemical engineering profession, the book is indispensable on account of the disclosed course outlines and teaching methods developed by experience. It should also be of value to men in industry who are trying to keep abreast of the broad field while becoming expert in a part of it. Students reading the book will find where some of their professors are getting material not in the textbooks. Anyway you take it, the book is a big two dollars' worth. It weighs more than two pounds.

(Continued on page 22)



#### HERE'S WHAT'S IN IT

**Description of the HASTELLOY Alloys**—A brief summary of the chemical composition and physical properties of the four alloys: A, B, C, and D.

**Resistance to Corrosion**—Easy-to-read tables show the resistance of each of the HASTELLOY alloys to 8 common corrosive media.

**Physical and Mechanical Properties**—Four pages of tables give properties at room temperature and also at elevated and sub-zero temperatures. Graphs compare the properties of HASTELLOY alloys with those of other metals.

**Available Forms**—HASTELLOY alloys can be supplied as conventional and precision investment castings; hot-rolled bar stock, sheet, and plate; wire, tubing, and welding rod; also, pipe and fittings.

**Fabricating Procedures**—The proper procedures for welding, heat-treating, hot-working, cold-working, surface preparation, machining, and grinding the alloys are given.

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- production of chemicals, petroleum, textiles, plastics,
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- Resistant Alloys."

- The trade-marks "Haynes" and "Hastelloy" distinguish products of
- Union Carbide and Carbon Corporation.

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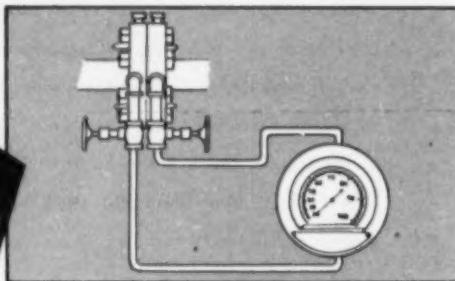
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#### J. ALBERT WOODS HEADS COMMERCIAL SOLVENTS

J. Albert Woods was recently elected president of Commercial Solvents Corp., New York, N. Y., at a special meeting of the board of directors. For many years Mr. Woods has been active in the agricultural chemical field, with experience in both production and sales. Prior to going with Commercial Solvents, Mr. Woods was president of Wilson & Toomer Fertilizer Co., manufacturers of heavy chemicals, fertilizers and insecticides. He was also associated with the Armour Fertilizer Works, Chilean Nitrate Sales Corp., and W. R. Grace & Co.

#### SMITH HEADS KELLOGG; OTHER OFFICERS NAMED

Warren L. Smith, former senior vice-president, has been elected president of The M. W. Kellogg Co., New York, N. Y. In his new capacity he succeeds Harold R. Austin, who is retiring.

In retiring Mr. Austin leaves an association formed 47 years ago when he joined The M. W. Kellogg Co., as an engineer-salesman.

W. L. Smith, Kellogg's new president, is a chemical engineer who has been associated with the company since 1937.

At the annual meeting of the board of directors when these changes were announced, the executive staff was enlarged and other officers named.

#### NAT. FOAM CONSOLIDATES AT WEST CHESTER

National Foam System, Inc., supplier of foam fire-fighting equipment and chemicals, recently closed its sales offices which it had maintained in the Packard Building in Philadelphia, Pa., and relocated it with all its manufacturing, research, and engineering facilities at West Chester, Pa. At this location a new laboratory has been constructed to give increased research facilities, the engineering department has been enlarged, and entirely new office facilities provided. This consolidation, it is believed by the company will enable the organization to give more efficient service.

#### MEETING OF NAT. SOC. PROFESSIONAL ENGRS.

The National Society of Professional Engineers will hold its annual meeting at the Hotel Statler in Boston, Mass., on June 8, 9 and 10, 1950. Sessions are open to all engineers and the general public.

(More Industrial News on page 23)



# in project engineering



**look to these Lummus men for worldwide performance**

## The Lummus man

engaged in project engineering has a well diversified background of practical experience. Directly from a mechanical course at college, he entered the petroleum field and acquired his early experience on an oil company, either in the Engineering Department or in the Operating Department. He joined Lummus approximately 15 years ago, where his experience was extended covering all phases of engineering from laboratory, through design and planning to actual field construction. Keeping abreast of developments, he has maintained his standing as a licensed professional Engineer.

In his wide field of project engineering are included many of the world's outstanding refinery installations as well as petroleum chemical units.

The Lummus Project Engineer is "at home" with operations in foreign fields. He has a broad knowledge of the unique problems encountered in Europe, the Near East, India, the Orient, Latin America, and Canada, as well as in the U. S. A. Project Construction in isolated locations presents unusual difficulties in connection with problems of water supply, water disposal, housing facilities, personnel, etc., problems which the Lummus Engineer has handled successfully.

Your Project at Lummus will receive the attention of those Engineers whose experience will best fulfill your specific needs. Frequent requests by customers for reassignment of the same Engineers for "repeat" jobs is the best evidence of their competence.

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Esquina Los Gradielos, Caracas, Venezuela



## MARGINAL NOTES

(Continued from page 18)

### Admirable Perry

Chemical Engineers' Handbook. John H. Perry, Editor and Coauthor. (Third Edition.) McGraw-Hill Book Co., New York. (1950) 1942 pp. \$15.00.

THE new third edition of the Chemical Engineers' Handbook is now published. Through the first edition of 1934 and the second edition of 1941, this handbook has become a standard reference book in the chemical engineering profession, and also a standard text in some 125 colleges and universities.

The most noticeable change in this edition is the new format. The appreciably larger page size,  $7\frac{1}{2} \times 10$  in. (the second edition page size was  $4\frac{1}{2} \times 7$  in.) has permitted the use of larger graphs and other illustrations. All illustrations have been newly prepared for this edition with increased legibility. The page format is double column which increases readability.

It is obviously impossible to review in detail each of the 30 sections of this handbook without exceeding the space available here. However, the Editor's preface states that:

The following sections have been thoroughly revised: Flow of Fluids; Heat Transmission; Solvent Extraction; Mixing; Adsorption; Physical and Chemical Data; Physical and Chemical Principles; Mathematics; Mathematical Tables and Weights and Measures; Humidification, Dehumidification, Spray Ponds, and Cooling Towers; Fuels; Electrochemistry; Refrigeration; Electricity and Electrical Engineering; Materials of Construction; Mechanical Separations; Safety and Fire Protection, and Accounting and Cost Finding.

The following sections have been rewritten and expanded: Size Reduction; Power Generation; Gas Absorption; Distillation; Plant Location; Drying; Movement and Storage of Materials; Process Control; and High Pressure Technique. In addition, the following chapters have been rewritten and expanded: Low-Temperature Refrigeration and Processes; Miscellaneous Methods of Mechanical Separations; and Sublimation.

The following sections have been deleted in the present edition in order to use the space for material believed to be of greater value in this handbook: Reports and Report Writing and the section formerly devoted to Indicators, Qualitative Analysis, and Organic Chemistry. The material on Indicators, however, is retained in another section after proper revision.

The section on General Theory of Diffusional Operations is an able presentation of the theory of these operations and is placed immediately before the major separate sections on Distillation, Gas Absorption, and Solvent Extraction, all of which contain the special theory

applicable to each of these unit operations. At the same time, the general theory is given in each of these unit operations sections so that it is not necessary to turn to the General Theory section for, say, a problem in Distillation.

The new section on Furnaces and Kilns, prepared by four chemical engineers of different types of experience appears to be a good introduction, and more, on a subject which has not too extensive a literature. Adequate references to the best publications on these subjects should be particularly satisfying.

Size enlargement is treated, and is the more valuable since this is a growing art and size reduction has long overshadowed size enlargement.

The section on Distillation has added chapters on such important subdivisions as: azeotropic, multicomponent, and extractive types of distillation operations. Also, there is an excellent chapter on the increasingly important operation of molecular distillation.

Dialysis is treated for the first time in this handbook and while the space devoted to it is relatively small, it is probably adequate in view of the present development and use of this operation.

Finally, mention must be of the Index. The number of entries is far larger than in previous editions and the use of synonyms and equivalents will erase the usual gripes, or many of the gripes, about inadequate indexes, that are most often heard about technical books and about handbooks, encyclopedias, and the like particularly.

The cost of the edition has been increased from \$12 to \$15, but a classroom text is available at a reduced price. Even with the increased cost this handbook represents a great deal of book.

### Cineole to Dextrose

Encyclopedia of Chemical Technology — Volume 4. Editors Raymond E. Kirk and Donald F. Othmer. The Interscience Encyclopedia, Inc., New York, N. Y. (1949) 969 pp. \$20.00 a volume.

Reviewed by F. J. Van Antwerpen, Editor, Chemical Engineering Progress.

THE fourth volume of the Encyclopedia of Chemical Technology has now been off the press some few months. An evaluation of its contents, which goes from Cineole to Dextrose reveals that it has the same high quality as its predecessors.

There is an excellent section on data correlation and a long section on corrosion. Other subjects covered in extensive detail are—Citric acid, Clays, Coal, Industrial Coatings, Colloids, Color

Measurement, Conveying, etc. It is the Conveying Section which points up a fact about the volumes that this reviewer had not noticed before, that is, engineering technology is coming in for a great deal of attention in these volumes. Most of the previous volumes have dealt with the chemistry and process flow of various industries. The treatment given to Conveying indicates that the engineering and unit operations of the chemical field are going to get thorough treatment. This indicates a rather important addition to the literature of chemical engineering unit operations. The number of proposed volumes in the series has been increased from 10 to 12.

### Big Undertaking Carries On

Electronic Engineering Master Index, 1947-1948. Electronics Research Publishing Co., Inc., New York 13, N. Y. John F. Rider, Editor. 339 pp. + xiii. \$19.50.

THIS is a subject index to the contents of electronic and allied engineering publications printed throughout the world. The titles of all articles appearing in foreign-language magazines have been translated into English. It contains more than 18,000 new entries. Two entirely new sources for reference have been included in the present volume, the 5,500 electronic and allied patents issued by the U. S. Patent Office during 1947-48, and the declassified documents published by the U. S., British, and Canadian governments. Patents are listed in numerical sequence under subject headings.

### Books Recently Published

V.I.V. Jubilee 1928-1948. Vlaamse Ingenieursvereniging, Torengebouw VIII, Schoenmarkt 31, Antwerp. 375 pp. including 52 studies in Dutch, French or English languages totaling 350 figures. Contains papers presented at the First International Congress for Harbour Engineering which took place in Antwerp, June 16-19, 1949. Price 500 Belgian Fr.

Organic Syntheses, Vol. 29. Cliff S. Hamilton, editor in chief. John Wiley & Sons, Inc., 440 Fourth Ave., New York 16, N. Y. (1949) 119 pp. \$2.50.

Proceedings of Annual Meeting 1949. Published by Engineering College Research Council (A.S.E.E.) at the College of Engineering, State University of Iowa, Iowa City, Iowa. Meeting held June, 1949, Rensselaer Polytechnic Institute, Troy, N. Y. John I. Mattill, Editor. 140 pp. \$2.00. In addition to an unusual group of papers on engineering instrumentation the Proceedings includes other papers dealing with the nation's engineering research problems.

(More Marginal Notes on page 25)

## CHEMISTS HONOR KRAUS

At a general assembly of the ACS held in connection with the society's 117th national meeting, Prof. Charles A. Kraus was awarded the Priestley Medal for his services to chemistry. The Brown University scientist, who is a director and former president of the society, will receive the medal at the society's fall meeting in Chicago.

Although he retired from the Brown faculty in 1946 he has continued his work in the university's Metcalf Research Laboratory. During World War II Dr. Kraus assisted in the purification of uranium salts for the atomic bomb project, and he also developed oxygen rebreather equipment for Navy aircraft, for which he received in 1948 the Navy Distinguished Public Service Award.

Professor Kraus is the recipient of many medals and honors, among them the Willard Gibbs Medal of the ACS Chicago section for his research on the theory of solutions, and the Theodore William Richards Medal of the society's Northeastern section for his work in this field; also the William H. Nichols Medal of the ACS New York section and the Franklin Medal of the Franklin Institute, Philadelphia.

## DU PONT'S FILM DIVISION

The Du Pont Company recently created a new department for research, production and sales for all products currently handled by the Cellophane division of the company's Rayon department. The new organization, to be known as the Film Department, will have as its general manager Donald F. Carpenter, former chairman of the National Munitions Board and long-time Du Pont employee.

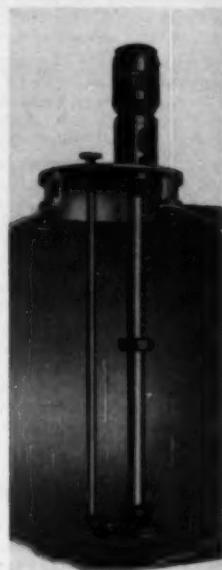
The step, which became effective April 1, was taken because the business of the Cellophane division has expanded since the war.

## GLOSSARY OF NUCLEAR SCIENCE PREPARED

The National Research Council Conference on Nuclear Glossary has published two sections of a Glossary on Nuclear Science and Technology: the 5th Section on Chemical Engineering, and the 6th Section on Biophysics and Radiobiology. Both are available at a price of 60 cents each, from either the National Research Council, Washington, D. C., or the American Society of Mechanical Engineers, 29 West 39th St., New York 18, N. Y., who are printing the Glossary for the NRC.

The section on Chemical Engineering contains only eight pages of actual terms of glossary and 20 pages of alphabetical arrangement of terms which refer to other sections yet to be published.

(Right) Structural details of Lawrence Vertical Chemical Pump.  
(Below) Vertical Chemical Pump mounted inside of tank.



## VERTICAL CHEMICAL PUMPS

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# SECRETARY'S PAGE

S. L. TYLER

THE Executive Committee met at the Office of the Institute on April 6 and after taking care of the routine matters assigned to it by Council proceeded with a discussion of many problems which received further attention at the Council meeting the following day.

The Council met on April 7, 1950, in Room A, The Chemists' Club, in New York City. Of the 17 members of Council, 14 were present. After approving Minutes and receiving recommendations of the Executive Committee regarding action on routine matters the Council proceeded to the business of the meeting.

One important item was discussed at some length, namely, the activities of the Committee of Engineers Joint Council on National Water Policy. This committee is making a thorough study of the situation regarding water as a natural resource and has been requested to work closely with the President's

Water Resources Policy Commission. Council voted to appropriate approximately \$250, which represents the Institute's share of the expected additional expense of this Committee.

A special committee of Council which studies committee reports and is referred to as the Committee on Committees presented a complete report which emphasized the recommendations and comments of the committee chairmen.

Upon recommendation of the Student Chapters Committee, J. S. Walton, Chairman, the formation of a student chapter at Pennsylvania State College was approved.

The attention of Council was called to the General Discussion on Heat Transmission which will be held in London, September, 1951; an invitation to participate had been received. Thomas B. Drew was appointed as our representative to keep in touch with develop-

ments on this Conference and report to Council.

The Auditor's Report for 1949 was received and approved and it was ordered that a summary be published at an early date.

Several other matters were discussed by the Council but no final action was taken so the report on these will be given later.

F. J. Van Antwerpen, editor and business manager of *Chemical Engineering Progress*, introduced a novel note into the meeting with his presentation of the report on the publication of Chemical Engineering Progress since its debut in 1947. The report was accompanied by slides which showed the course of progress over the three years and supplied other data which brought members of the Council up to date on this vital aspect of A.I.Ch.E. activity.

## CANDIDATES FOR MEMBERSHIP IN A.I.Ch.E.

The following is a list of candidates for the designated grades of membership in A.I.Ch.E. recommended for election by the Committee on Admissions.

These names are listed in accordance with Article III, Section 7, of the Constitution of A.I.Ch.E. which states:

Election to membership shall be by vote of the Council upon recommendation of the Com-

mittee on Admissions. The names of all applicants who have been approved as candidates by the Committee on Admissions, other than those of applicants for Student membership, shall be listed in an official publication of the Institute. If no objection is received in writing by the Secretary within thirty days after the mailing date of the publication, they may be declared elected by vote of Council. If an objection to the election of any candidate is received by the Secretary within the period specified, said objection shall be referred to the Committee on Admissions, which shall investigate the cause for such objection, holding all communications

in confidence, and make recommendations to the Council regarding the candidate.

Objections to the election of any of these candidates from Active Members will receive careful consideration if received before June 15, 1950, at the Office of the Secretary, American Institute of Chemical Engineers, 120 East 41st St., New York 17, N. Y.

### APPLICATIONS FOR ACTIVE MEMBERSHIP

John L. Aitken, Hoquiam, Wash.  
Craig W. Angell, Belmont, Mass.  
Kenneth D. Ashley, Stamford, Conn.  
Allen I. Barry, Eastport, Me.  
J. R. Barsalou, Jr., Baytown, Tex.  
Oral E. Beber, Crystal Lake, Ill.  
V. O. Bonnichsen, Argo, Ill.  
Akbar F. Brinsmade, Jackson Heights, N. Y.  
L. E. Carlsmith, Westfield, N. J.  
Woodrow W. Cerf, Argo, Ill.  
Mario T. Cichelli, Wilmington, Del.  
Calvin L. Dickinson, Pasadena, Tex.  
Thomas F. Doumani, Wilmingtnon, Calif.

George P. Ferrigni, No. Plainfield, N. J.  
M. Clark Fogle, Pittsburgh, Pa.  
J. Lawrence Gray, Cartersville, Ga.  
John H. Hall, New York, N. Y.  
Raymond E. Hanning, St. Marys, Ohio  
John H. Holmes, Louisville, Ky.  
B. W. Jesser, Hackensack, N. J.  
John C. Jubin, Jr., Drexel Hill, Pa.  
Donald A. Justus, Detroit, Mich.  
Harold S. Kemp, Wilmington, Del.  
Gordon W. Kidder, Bloomall, Pa.  
Neal V. Lamb, Bartlesville, Okla.  
Rolf Lindenayn, Jr., Harrison, Ohio  
Robert Lobstein, Forest Hills, N. Y.

### Horace E. Lantz, Ponca City, Okla.

John J. McKetta, Jr., Austin, Tex.  
Herbert Herman Meier, Baytown, Tex.  
Melvin Nord, Detroit, Mich.  
Richard B. Olney, Oakland, Calif.  
Edward P. Pearson, Tiffin, Ohio  
William Pechenick, Brooklyn, N. Y.  
Prentiss W. Reeves, Buffalo, N. Y.  
David Rosenberg, Niagara Falls, N. Y.  
Edward W. Samoden, Piney River, Va.  
William E. Schaefer, Brooklyn, N. Y.  
Marshall Sittig, Detroit, Mich.  
George V. Slottman, New York, N. Y.  
Homer B. Terry, Olympia Fields, Ill.

Paul R. Walton, Paulsboro, N. J.  
A. Roland Worrall, Baltimore, Md.

### APPLICANTS FOR ASSOCIATE MEMBERSHIP

Herbert C. Bendel, Parma Heights, Ohio  
Michael G. Dalich, Sterlington, La.  
A. C. Goodman, Los Angeles, Calif.  
Bailey K. Kallay, Wyandotte, Mich.  
Henry S. Myers, Brooklyn, N. Y.

### APPLICANTS FOR JUNIOR MEMBERSHIP

Frederic N. Alderman, Hatboro, Pa.

Richard A. Bailey, Port Arthur, Tex.	chester, N. Y.	N. Y.	Nelson Roberts, Lawrenceburg, Ind.
Robert G. Bailey, Harrisonburg, Va.	John F. Fletcher, Pullman, Wash.	William Lazor, Jr., Wilmington, Del.	Donald A. Runzman, Seattle, Wash.
John H. Ballard, Los Angeles, Calif.	Edward D. Fox, Los Angeles, Calif.	James Lee, Minneapolis, Minn.	Kenneth D. Sales, Charleston, W. Va.
Marcel Alexander Ballouz, Morgantown, W. Va.	Arthur E. Fransen, Chicago, Ill.	William S. Lenihan, Jr., Oak Ridge, Tenn.	Robert E. Salveter, Jr., Marion, Ind.
Bion D. Barger, Jr., Seattle, Wash.	William J. Frink, St. Albans, W. Va.	J. O. Philip Lindahl, Bartlesville, Okla.	Richard L. Schmitz, Brentwood, Mo.
Bernard Bark, New Brunswick, N. J.	Harry W. Fritts, New Kensington, Pa.	Franklin S. Looney, College Station, Tex.	Robert F. Schnaith, Whitling, Ind.
C. Robert Bickling, Wilmingtton, Del.	Gerald W. Giles, Chicago, Ill.	Lewis H. Mahony, Rochester, N. Y.	Burnett J. Schulz, Beaumont, Tex.
J. B. Bingeman, Minneapolis, Minn.	Robert D. Gleichert, Barberton, Ohio	George H. Maringas, Harvey, Ill.	Hillis H. Sick, Hammond, Ind.
Philipp W. Binzel, Whiting, Ind.	John J. Gorman, Huntsville, Ala.	J. L. Martine, St. Louis, Mo.	Raymond A. Speed, Baytown, Tex.
Earle P. Bisher, Kingston, Pa.	Bruce F. Gross, Pittsburgh, Pa.	John M. Mason, Seattle, Wash.	Alan H. Stark, Cleveland, Ohio
Hugh W. Black, New Orleans, La.	Kenneth W. Guebert, Freeport, Texas	William F. McIlhenny, Freeport, Tex.	Fred E. Stuart, Jr., La Grange, Ill.
Stuart S. Brown, Pittsburgh, Pa.	Alton S. Hall, New Orleans, La.	Allan S. McLatchie, Calgary, Alberta	Roger W. Tate, Madison, Wis.
Leonard A. Caplan, Blacksburg, Va.	James W. Harper, Beaumont, Tex.	Laurent Michel, Cambridge, Mass.	Rodman B. Teeple, Jr., Wilmington, Del.
John R. Cherer, Munster, Ind.	Edward R. Hayes, Whiting, Ind.	William R. Millard, Ithaca, N. Y.	Edwin C. Tolocsko, Chicago, Ill.
Oleg G. Cherny, New York, N. Y.	Waldemar R. Hertwig, Whiting, Ind.	Roy W. Miller, Hammond, Ind.	F. A. Verser, Jr., College Station, Tex.
Revere G. Counselman, Bronxville, N. Y.	John R. Hill, Columbus, Ohio	Jack R. Moseley, Port Arthur, Tex.	Carl E. van Waarden, Lawrence, Kansas
John H. Cusack, State College, Pa.	Dwight S. Hoffman, Moscow, Idaho	Edwin W. Neildridge, New York, N. Y.	Theodore Y. Wakai, Iowa City, Iowa
J. V. Day, Ville Platte, Pa.	Roger S. Holcomb, Munster, Ind.	James R. Nevin, St. Louis, Mo.	K. H. Wanderer, Chicago, Ill.
George Demitrick, Bronx, N. Y.	John F. Honstead, Topeka, Kansas	Robert J. Newman, Wichita Falls, Tex.	Edward A. White, Urbana, Ill.
Eugene P. L. dePrusse, Cloquet, Minn.	Howard Lee Horne, Blacksburg, Va.	Bernard Arthur Paulson, Alma, Mich.	William E. White, Harvey, Ill.
James P. Derouin, Richland, Wash.	M. William Jacunski, Bloomfield, N. J.	Ralph F. Peak, Johnstown, Col.	George M. Wilmsen, Madison, Wis.
Rollins E. Dobbin, Stoneham, Mass.	William C. Johnson, Kalamazoo, Mich.	Roy D. Peak, Denver Col.	W. H. Wingate, Jr., Spartanburg, S. C.
Edmund C. Fenstad, Santa Ana, Calif.	Fred W. Kemp, Saltville, Va.	Dudley P. Penick, Dallas, Tex.	Harold S. Wood, Whiting, Ind.
Emmett John Ferretti, New York, N. Y.	Howard K. Kothe, Brooklyn, N. Y.	Troy F. Reid, Kingsport, Tenn.	I. J. Wright, Jr., Houston, Tex.
L. Daniel Fessenden, Roc-	George Kuruse, New York,	David J. Rex, III, Painesville, Ohio	

## INDUSTRIAL NEWS

(Continued from page 12)

working party would not be profitable, since the sample already scrutinized by the working party has revealed that relatively little technology of major importance is being withheld.

4. That the search of the patent files was of sufficient interest to warrant continuing the test program, especially to study the complete technology of a major atomic energy process, such as that being carried on at Y-12.

The trial program was set up by the AEC in response to the recommendation of an Industrial Advisory Group that information still classified, but potentially declassifiable and of special interest to industry, should be surveyed and declassified.

To assist in developing the program, a temporary advisory committee of representatives of professional societies and the business press was appointed. The advisory committee made recommendations on how to proceed with the program and recommended candidates for membership in the working party. Members of the working party were given in C.E.P. February, 1950, p. 14.

## MARGINAL NOTES

(Continued from page 22)

**Boron Trifluoride and Its Derivatives.** Harold Simmons Booth and Donald Ray Martin. John Wiley & Sons, Inc., New York 16, N. Y. VIII + 315 pp. \$5.00.

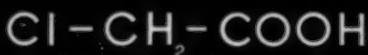
Reviewed by Harold C. Weber, Chemical Engineer, Milton, Mass.

A GOOD monograph should not only cover the field completely, but also should be authoritative and convenient to use. This monograph fulfills these three requirements. In their endeavor to present a complete and authoritative picture of the knowledge pertaining to boron trifluoride and its derivatives, the authors not only scanned *Chemical Abstracts* page by page from its beginning and reviewed the usual texts, but, in addition, enlisted the aid of several outstanding experts and consulted the files of 18 of the larger companies in the United States interested in the production and commercial utilization of boron trifluoride. The material presented includes everything available to the authors up to Jan. 1, 1948. The information is conveniently arranged in eight chapters having the following headings:

1. History and Preparation
2. Physical Properties
3. Chemical Properties
4. Coordinating Power of Boron Trifluoride
5. Fluoboric Acids and Their Salts
6. Boron Trifluoride as a Catalyst
7. Analysis of Boron Trifluoride and Its Compounds
8. Practical Handling of Boron Trifluoride

Free use is made of tables and easily understood charts. In practically every case where a chart is used, the experimental points are plotted on the drawings enabling the reader to judge immediately how well the curves presented fit the data and over what ranges the curves have been extrapolated. Such a procedure is to be commended but all too often is not followed. To aid the reader in locating the exact information he may desire, four indices have been provided: the first contains 973 references arranged alphabetically, for the most part by authors, but in a few cases, by company name; the second is the usual author index; the third is the subject index, the latter covering 14 pages, its length affording a clue as to its completeness; the fourth is a formula index. Several spot tests using the indices gave evidence they were unusually complete.

# Chloroacetic Acid



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Ethyl Chloroacetate

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# DATA SERVICE

## EQUIPMENT

**1 • RATOTHERM AND RATOGAGE.** Fischer & Porter Co. add to their line of new temperature and pressure instruments. The temperature instruments (Ratotherm) have thermal systems filled with liquid, gas, or a combination, and the series covers ranges between  $-125^{\circ}$  F., and  $+1000^{\circ}$  F. The Ratotherm system uses capillary tubing for transmittal of the change induced by temperature differences. Tubings, which are bronze, steel, stainless steel, etc., can be rubber covered, lead covered or plastic coated for resistance to corrosives. The Ratogage pressure instruments are of three types: bellows pressure element, a multiple diaphragm pressure element and a helical pressure element. With the three types measurements from 4 to 10,000 lb./sq.in. gage are possible. Recorders and control systems are described in the same catalog.

**2 • ALLOY IDENTIFICATION.** From the Electro-Chemical Instrument Laboratories, a portable metal alloy identification instrument known as the Electrosport. Battery instrument, weighing less than 5 lb., the equipment makes use of the inherent differences in the surface films on metals and alloys to identify them by electrolytic means. It will sort alloys of aluminum, copper, gold, iron, lead, nickel and stainless steels. Various electrolytes are used for the identification which can be rapidly read from a millivolt meter.

**3 • PLUG VALVE LUBRICATOR.** For plug valves from  $\frac{1}{2}$  in. to 20 in. in size, a new lubricator of the Delta Engineering Sales Co. A measured amount of lubricant is forced into the plug valve lubricating channels each time the valve is opened or closed.

**4 • SPRAY NOZZLE.** A spiral spray nozzle, to give wide-angled sprays, with capacities of  $\frac{1}{2}$  to 2 gal./min., and another from  $1\frac{1}{2}$  to 4 gal./min. is new to the Bete Fog Nozzle Co. Produces a  $180^{\circ}$  umbrella spray pat-

tern, with low pressure head. Spray nozzle is cleaned by means of a removable pin.

**5 • ELECTRIC STEAM PLANT.** Aiding the new technique of spray painting with steam instead of air, the Livingstone Engineering Co. has designed an all-electric steam power plant, plus a 100 lb./sq.in. boiler. The boiler will handle from 1 to 10 spray guns. The unit, which is designed for industrial users of spray-painting equipment, includes an electric superheater, thermostatic control, boiler feed pump, motor and controls.

**6 • CONTINUOUS CONCENTRATOR.** Bowen Engineering, Inc., to complement its spray dryer, has a new Stabilizer, which is a continuous concentrator for use with heat-sensitive materials to bring them to higher degrees of concentration. The body of the Stabilizer is an insulated-steel jacket. The inner wall is a horizontal cylinder against which a rotor arm is carried on a centrally located shaft driven at low speed. The material is driven through a feed pipe at one end of the cylinder and a discharge pipe removes the concentrate at the opposite end. Vapor discharge through a stack. Available in 6 sizes with an evaporation rate of from 600 to 12,000 lb./hr.

**7 • PULVERIZER.** A swing hammer mill for fine grinding, granulating, or wet milling, for usual application

in the chemical industry is now being manufactured by the Pulva Corp. The mill uses twin screws to feed the material to the face of the hammers and can handle pieces up to 3 in. in size.

**8 • STEAM BOILER.** A new steam boiler for heavy oils and gas, and available in sizes of from 15 to 500 hp., is a recent development of the Cleaver-Brooks Co. The new model has a rotary burner which provides flexibility for burning the oils or gases. Single low-speed blower furnishes combustion air. The change over from oil to gas or the reverse can be done in less than a minute. The model uses the Cleaver-Brooks four-pass fire tube design.

**9 • VENT VALVE.** Crane Co. has a new automatic vent and drain valve. The new mechanism makes use of the ball-type seat instead of the customary disc. Used on water- or oil-piping systems to remove entrapped air, or in compressed air systems to remove water. Sizes available for air requirements up to 150 lb./sq.in. and water up to 125 lb./sq.in.

**10 • pH METER.** A line-operated pH meter with reproducibility to 0.03 pH is a recent development of Coleman Instruments, Inc. Operates on 95 to 130 v., 50/60 cycles. The electrode system permits use of a variety of special electrodes. Instrument reads directly in pH.

**11 • HEAT EXCHANGER.** An all-

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## Chemical Engineering Progress Data Service

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Company \_\_\_\_\_

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# DATA SERVICE

cuprous standardized exchanger, with a removable tube bundle, is in quantity production at Ross Heater & Mfg. Co., Inc. Unit has a packed floating head and is available in single or two-pass construction. All parts are standardized and mass-produced and continuously carried in stock. Bulletin shows construction details, gives dimensions, weights, etc.

**12 • ASPIRATOR.** For engineers in the food, feed, and chemical industries, Sprout, Waldron & Co. have designed a new, single-disc aspirator for removing light impurities from products. The gravity-fed products drop through a feed sleeve to a revolving iron disc revolving at a speed determined by the product. The stock spreads out thinly into an air stream, the light material floating off for cyclone collection.

**14 • HUMIDITY RECORDER AND CONTROLLER.** For process industries needing humidity control during processing, Weston Electrical Instrument Corp. developed a controller which automatically regulates the wet-bulb (relative humidity) for which it is set regardless of fluctuations in the dry-bulb.

**15 • PLASTIC COATING.** For lining petroleum and chemical tanks, Glidden Co. has Vinyl-Cote which is impervious to caustic, sour crude and most acids. Unaffected by oils, greases and solvents, the vinyl poly-

mer is put on in five different-colored layers. Usable up to temperatures of 180° F.

**16 • SAFETY HOOD.** General Scientific Equipment Co. is in production with a new safety hood having an improved rubber which will withstand oils, caustics, acids, etc., and protects against extreme temperature and light metal splashes. Has a plastic window for visibility and may be worn with goggles or a respirator.

**17 • PROCESSING MILL.** A new stainless steel mill, with a capacity of 8 to 20 gal./hr. and slotted for precise laboratory work permitting no contamination, has recently been designed by the Morehouse Industries. The mill is driven by a 3-hp. motor and is 14 in. in diameter and 3 ft. high. Used are special corundum stones to obtain the grinding.

## CHEMICALS

**20 • CITRACONIC ANHYDRIDE.** A 16-page pamphlet on citraconic anhydride which includes all the physical properties, reactions, preparation, etc., that the Smith New York Co. has been able to trace in the literature. Chemical reactions, compounds, etc.

**21 • POLYAMIDE RESIN SUSPENSoids.** An 8-page data sheet by General Mills, Inc., on its water dispersions of polyamide resin. Polyamide resin

is a condensation of dimerized vegetable oil acids with ethylene diamine. Gives physical properties, compounding, solubilities in solvents, etc. Suitable plasticizers, etc. Suggested uses include adhesives, protective coatings, paper, binders, textile, leather, etc.

**22 • POLYETHYLENE-LINED DRUMS.** Schori Process Division now offers polyethylene-lined 30- and 50-gal. Hackney open-head seamless barrels. The lining is 1/32 in. thick but 1/8 in. linings are also available. The Schori Process Division developed the Flame Spray process (see March Data Service Item No. 5).

**23 • NITROGEN SOLUTIONS.** For the fertilizer field, Spencer Chemical Co. has a pamphlet describing Spensol solutions which are water solutions of solid ammonium nitrate and anhydrous ammonia. The pamphlet describes solution types, charts of physical properties. Tables detail quantities for ammoniation. The complete handling of the solutions at the plant, plus fertilizer formulation, precautions to take in handling the material, ammoniation equipment, etc., are all covered.

**24 • FIRE-RETARDANT.** To meet the requirements of flame-resistance of the Army Quartermaster, Federal Specification, and National Bureau of Standards, Monsanto Chemical Co. has introduced a new low-cost chemical for imparting fire-retardant properties to all types of cellulosic fabrics. A 10-page bulletin gives properties, application to fabrics, preparation for treatment, etc.

**25 • DICYCLOPENTENYL ALCOHOL.** Rohm & Haas have in pilot plant production dicyclopentenyl alcohol obtained by the hydration of dicyclopentadiene. It is insoluble in water and miscible in all proportions with common organic solvents. Its derivatives have potential use in the coating fields.

**26 • RESORCINOL.** The chemical division of Koppers Co., Inc., has a new, comprehensive 40-page technical bulletin describing the chem-

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# DATA SERVICE

ical and physical nature and uses of resorcinol. Typical physical data are given plus commercial information, grades available and their specifications, toxicology, uses (antioxidants, cosmetics, dyestuffs, etc.), chemical reactions, plus an extensive bibliography.

**27 • FATTY ACIDS.** W. C. Hardesty Co., Inc., has a new 24-page fatty acid specifications catalog. The book covers the properties of stearic acid, oleic acid, red oil, hydrogenated fatty acids, distilled fatty acids, palmitic acid and glycerides. Technical data, such as color standards, composition of fats and oils, temperature conversion tables, etc.

**28 • RESIN GUIDE.** A second edition of American Cyanamid Co.'s Resin Guide devoted to tabulating the specifications for the resins it manufactures for use in paints, varnishes, lacquers and printing inks. It is a wall plaque with tab sheets giving the physical and chemical products of each resin—solubility, compatibility, drying schedules, plus colors, viscosity and other physical properties.

**29 • DURITE MOLDING COMPOUNDS.** The chemical division of the Borden Co. shows in pictorial fashion the applications of phenolic thermosetting molding compounds.

**30 • LIQUID BROMINE.** For the methods and materials for handling liquid bromine, the Dow Chemical Co. has a 22-page bulletin. It covers the safety precautions for dealing with the material in glass bottles, lead-lined drums, and tank cars. Also contains a section on materials of construction, control devices, storage tanks, pipe lines, etc.

**31 • LITHIUM CHEMICALS.** Foote Mineral Co.'s staff has prepared a 28-page booklet on lithium chemicals and their industrial application. The future of the element, the chemistry (which includes physical properties), chemical specifications of industrial salts, bibliography and industrial uses are well detailed.

**32 • CHLORINE HANDBOOK.** Diamond Alkali Co. offers a 44-page file-size technical manual on storage, handling, and use of chlorine. The book covers every phase of chlorine from the construction of the cylinders, tank cars, discharge valves, etc. Shows the proper way to handle the material, safety precautions, physical properties and enthalpy temperature diagram, etc.

## BULLETINS

**36 • STEEL INSTRUMENT VALVES.** For use on petroleum Christmas trees or small lines in petroleum and chemical processing plants, Edward Valves, Inc., are in production with a new forged-steel instrument valve which will withstand pressures as high as 6000 lb. Made of corrosion-resistant material such as carbon steel, 15% chromium, or 18-8 stainless, the new valves are available in globe or angle design in  $\frac{1}{4}$ -in.,  $\frac{3}{8}$ -in. and  $\frac{1}{2}$ -in. sizes. At 1000° F. pressure rating is 1500 lb./sq.in.

**37 • WELDING FITTINGS PRICE LIST.** A new and up-to-date price list of The Cooper Alloy Foundry Co., stainless-steel welding fittings, has recently been published by the company. Covers all types of fittings, elbows, return bends, tees, etc.

**38 • ROD MILLS.** Hardinge Co., Inc.,

has issued a revised bulletin on its rod mills for grinding and pulverizing. The bulletin shows the principles of the rod mill, plus construction details and applications to various metallurgical and industrial processes. Also shows auxiliary equipment for the huge mills which run from 3 to more than 1000 hp.

**39 • JACKETED PIPE AND FITTINGS.** For maintaining uniform temperatures in pipes carrying processing material, Hetherington & Berner, Inc., offer a catalog of pipes and fittings jacketed to carry heat transfer media. Fittings have a double wall forming an all-over jacket surrounding and insulating the interior. External jump-over pipes transfer heat-transfer media from one fitting to the next. Plug cocks, tees, strainers, valves, etc., are shown with dimensions.

**40 • PROCESS EQUIPMENT.** The Vulcan Copper & Supply Co. printed a new descriptive bulletin showing process equipment. Heat exchangers, columns, pilot plants, piping, extractors, evaporators, etc., are described briefly. Facilities of the company are illustrated and a story of their organization service from process engineering through equipment manufacture to plant erection and start-up, is described. Short description of continuous solvent extraction unit.

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Name \_\_\_\_\_ Position \_\_\_\_\_

Company \_\_\_\_\_

Address \_\_\_\_\_

City \_\_\_\_\_ Zone \_\_\_\_\_ State \_\_\_\_\_

**41 • STEEL BELT CONVEYORS.** For transfer of materials in the process industries, Sandvik Steel, Inc., has designed and built complete conveyor units of steel. Belts can be either high carbon or 18-8 stainless dependent on application. The stainless belts handle material up to 350° F. and the carbon belts up to 700° F. The belt is joined by means of a riveted lap joint. Described also, is a new water-bed conveyor for cooling materials. The top band of the belt passes over a trough of circulating water in which the pressure is just enough to raise the belt off the supports. Specifications for the full line are given, which range in size from 8 in. to 61 in. in width, and from 24-gage to 18-gage thickness.

**42 • 43 • PETRO-CHEM FURNACES.** Two bulletins from the Petro-Chem Development Co., Inc. No. 42 is a technical description of the radiant-convection iso-flow furnace which via description and drawings shows the construction of the furnace, placement of tubes, burners, etc. The second, No. 43, is a description of the iso-flow steam generator which follows much the same pattern. Test data of the steam generator are given in a table.

**44 • AIR-COOLED HEAT EXCHANGERS.** From J. F. Pritchard & Co., a descriptive folder of their Quintair air-cooled heat exchangers for condensing or cooling steam or process vapors, natural gas, lubricating oil, etc. Many arrangements of the unit are possible and are shown together with a brief description of its features.

**45 • GLASS PIPE.** Corning Glass

Works in production with a new industrial glass pipe. According to the company, it is of greater strength owing to a heat treatment, has closer tolerances on length, flatness, angularity and bow.

**46 • FIRE HAZARD INDEX.** Randolph Laboratories, Inc., has indexed in a pocket-size, 36-page book, a quick reference alphabetical listing of more than 590 chemicals, gas and common fire-hazard materials. It specifies which kind of fire-fighting agent to use.

**47 • FILTER DATA.** Charts showing the relative cost of filter area and various sizes of plates for the wood plate and frame, the metal plate and frame, and the metal recess type, plus data on the filter area and volumetric capacity, and weight of complete filter press in various metals or wood, are concisely printed in a new folder of D. R. Sperry & Co. Data cover in general, presses containing from 5 to 100 plates; tables give filter area, cubic foot of capacity, weight of plates, etc.

**48 • ROTARY KILNS.** Descriptions of Vulcan Iron Works kilns. Shows the continuous rotary-type, continuous rotary coolers and dryers; shows replacement parts, construction details. Also covers briquetting machines, castings and fabrications, vertical lime kilns, etc.

**49 • ANGULAR MIXER.** A 2-page loose-leaf insert of Troy Engine & Machine Co. describes its new angular mixers. At the option of the operator, the mixing tank itself revolves along with the U-shaped angular mixing agitator. Various speeds available and two capacities,

a 40-gal. and a 60-gal. mixer are described.

**50 • OIL FILTER.** For purifying lubricating and fuel oils used in stationary engines, the Hilliard Corp. in a file folder, explains a new R series oil filter. Cartridges are available with either fuller's earth or cellulose filtering materials. Capacities of flow from 1 to 16 gal./min. Complete data of performance of the filters.

**51 • HAMMER MILL.** A brief pamphlet on the Sprout-Waldron Model H.D. hammer mill, a new model of this company's line. It is designed for heavy duty and daily production schedules; 50 to 75 hp. directly connected; the rotor travels at 3500 rev./min.

**52 • STEAM GENERATORS.** The Ames Iron Works has a folder containing bulletins describing all its Amesteam generators. Contains about 30 pamphlets, all of the same general format but describing different units. Standard units available from 10 to 500 hp., pressures from 15 to 200 lb./sq. in., for use with light oil, gas, heavy oil, and combinations. Also explains construction, condensate units, etc.

**53 • CORROSION SERVICE PIPING.** Taylor Forge, in a 36-page booklet, develops an approach to corrosion and contamination in piping. The book begins with the description of iron-pipe size, then discusses the function of welding in corrosion service piping. One of the important tables in the book, aside from the dimensional data on all Taylor Forge standard fittings, is a table on the corrosion resistance of stainless steels and other alloys. A table of alloys and analyses, plus physical properties, rounds out the book.

**54 • CARBON MONOXIDE RECORDER.** Mine Safety Appliances Co. has a refinement of its standard carbon monoxide recorder and features a sensitivity which can be calibrated to cover a range from 0 to 500 p.p.m. of carbon monoxide.

**55 • CENTRIFUGAL PUMP.** The type G LaLabour pump is described in an extensive publication. It is a vertical self-priming centrifugal, directly mounted, and pump has no packing or mechanical seal. Detailed explanation of priming action as well as information on the installation and care of centrifugal pump. Also contains information on friction of water in pipes, operating information, etc.

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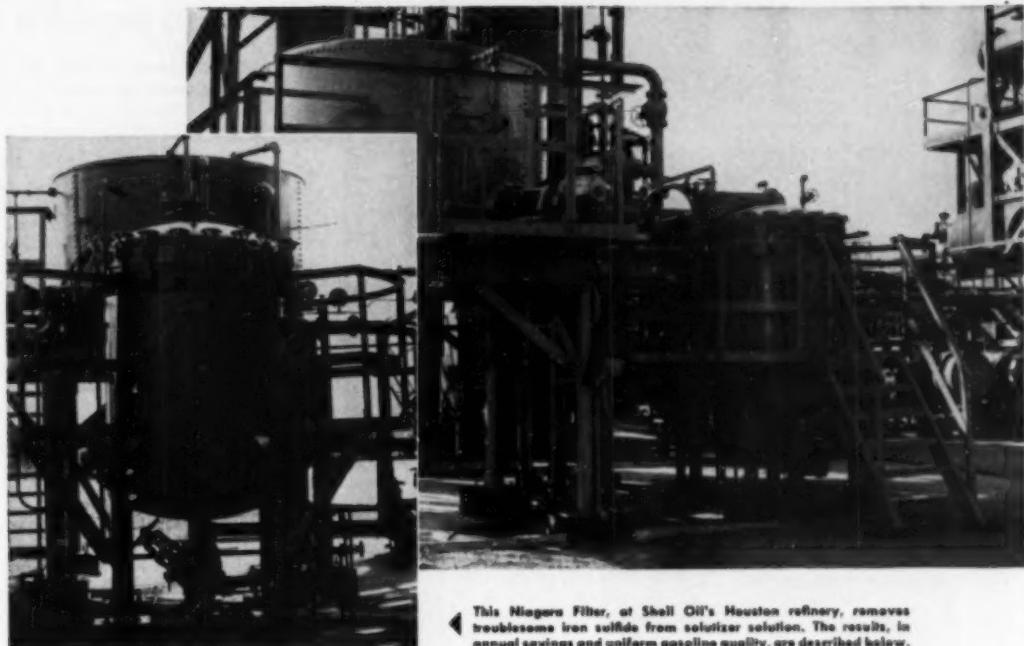
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## Chemical Engineering Progress

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This Niagara Filter, at Shell Oil's Houston refinery, removes troublesome iron sulfide from solutizer solution. The results, in annual savings and uniform gasoline quality, are described below.

## NIAGARA FILTER keeps Solutizer Solution "on-stream"

Shell Oil Company uses a Niagara Filter in its solutizer mercaptan extraction process and thereby effects "a significant annual saving."

Caustic solutizer solution is introduced into the extraction system, where it comes into contact counter-currently with the mercaptan-containing hydrocarbon fraction. The treated fraction and fat solutizer solution are withdrawn from opposite ends of the system.

A Niagara Filter was installed to remove the small amount of iron sulfide particles (averaging 20 microns) which gradually accumulate in fat solutizer solution. These insoluble materials in the system act as nuclei for troublesome emulsions and impair the effectiveness of the plant. The iron sulfide is contained in gasoline streams entering the solutizer plant.

The Niagara Filter has 16 stainless steel leaves with a total filter area of 322 sq. ft. It is delivering

solutizer solution free from iron sulfides, at a flow rate of 2700 GPH—and is doing this continually for a period of 64 hours before it is necessary to clean filter.

Continuous filtration helps to keep operation of the solutizer plant at high efficiency. Gasoline production remains uniformly high in octane number and tetraethyl lead susceptibility.

Niagara all-metal filters always save through elimination of filter cloths, simplicity of operation, increased filtration rates and long life of the stainless steel solderless filter leaves. Niagara filtration engineers are experienced in all types of filtration processes. They may be able to help you with your problems, and will be glad to test samples and tell you about pilot filter rental and other services. A letter from you outlining the problem will bring a prompt reply without obligation. Use the coupon below to order Bulletin G-447 for your files.

**Niagara Filter**  
CORPORATION

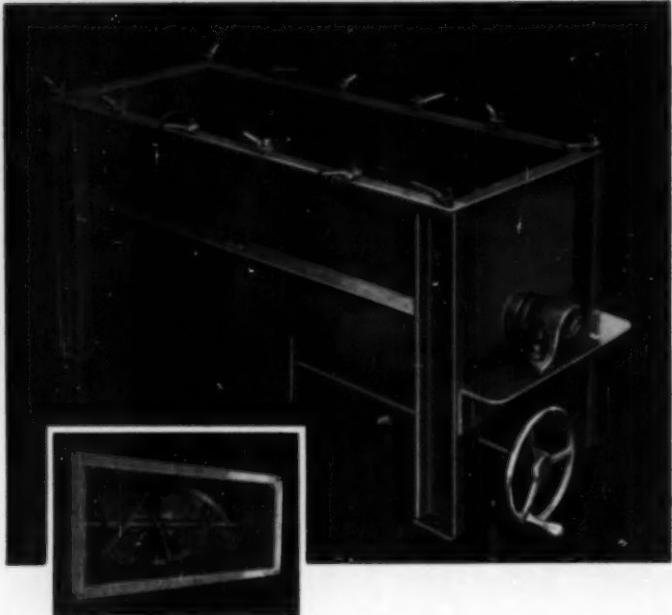
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# *Costly* AVOID <sup>A</sup> UNMIXED VOLUME



## Increase Mixing Efficiency and Cut Operating Costs with **READ Spiral Ribbon Blenders**

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Any unmixed or dead volume found in a mixer after the mixing operation has been completed is costly. This can be eliminated with a Read Spiral Ribbon Blender.

In a Read Blender, the counter-flow action of the spiral ribbon agitator insures rapid, efficient mixing without material build-up at the ends. Ground fillets on the all-welded agitator prevent build up of masses during mixing. At the discharge point, a liquid-type flush plug discharge gate eliminates any build-up of dead material at this point.

Read Spiral Ribbon Blenders are built with batch capacities of from 1 to 500 cu. ft. Special units are custom-built for larger capacities. Models can be supplied for operation under pressure or full vacuum, and may be equipped with temperature controlling jackets. Structural steel legs can be supplied in various heights to suit operating conditions.

Write for complete information on the Read Spiral Ribbon Blender for your particular application.

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## LETTER TO THE EDITOR

### Author Answers Critic on Engineers' Services

Sir:

Mr. Cox in the February, 1950, issue (p. 33), seems to disagree with my opinions in the December, 1949, issue (p. 33). His letter leads me to believe that we agree more than he thinks. We agree that engineers have the knowledge and ability to be of benefit to society. Though I respect preventive medicine and research too much to say that doctors are only called on when we are in trouble, and have referred to my employer's patent and legal departments on too many occasions to say the same of lawyers, I agree that doctors and lawyers are most useful in times of trouble. An engineer is not chiefly useful at such times. In the engineering field there are regions such as Mr. Cox mentions where an engineer can be of great value; I hope to get into one of these.

Mr. Wilde's editorial of last May, to which my original letter referred, pointed out that engineers were not fully recognized as professionals and supported the thesis that their contribution was as great as that of recognized professions. My difference with Mr. Wilde was only that I felt that most of the present engineering effort was not in fields as helpful to humanity as the efforts of doctors, lawyers, and ministers, which disappoints me since I think it could be. Mr. Cox claims I measure engineers by a higher "standard" than doctors and lawyers; I referred to no standard except public recognition. It is public recognition which rates us below the other professions—this may be a better evaluation than Mr. Wilde or Mr. Cox believes.

Here is why I believe this: Though doctors and lawyers are usually called in time of personal trouble, they have not limited themselves to curing people. The medical profession has sought and found the causes for many diseases, and drugs of much assistance in treatment. The legal profession serves as adviser in many legal matters before trouble occurs, and also is the major source of lawmakers and judicial interpreters of the law. Both these groups went to the source of the "trouble" with which they are generally associated, on their own initiative, and have helped humanity thereby.

Let us compare this performance with that of engineers. We are not called in time of trouble; we are rather the source of processes, products, and technological improvements in general which have caused change and in many cases trouble to groups of people, along with the important benefits of most technological

change. A fully professional approach to technological change should, I believe, have included consideration of the possible effects of improvement on groups of people, such as company employees, and the effects on the public in general. I don't think engineers have taken it upon themselves to do this. Many employers have started such consideration, and in some cases engineers have been put on such work, but chiefly by assignment rather than through a voluntary realization of the important effects of technology on the public. This is, I believe, an important indication of the lack of professionalism among engineering graduates. There are, of course, notable exceptions such as those in my first letter.

Mr. Cox agrees that some engineering effort could be expended along paths of more benefit to humanity; he says, "In matters of health and better living, there are a multitude of tasks that are awaiting attention of competent men." I also feel that, in such efforts as they do undertake, engineers would be acting more professionally to consider all the ramifications to society of the work they are undertaking.

*James B. Weaver  
Boston, Mass.*

March 8, 1950

#### **MARKETING COURSE AT PENN STATE**

A new course covering the various phases of the development, introduction and selling of new chemical products is to be given by The Pennsylvania State College, State College, Pa. This course, entitled, "The Marketing of Chemical Products," will first be presented in the Philadelphia area. Marcus Sittenfeld, a member of the staff of the school of chemistry and physics and a consulting engineer, will direct the course. Guest lecturers will present special phases of the subject.

Registration for the course is now open to qualified chemists, engineers and others. Further information can be obtained from Arthur K. Meyers, administrative head, The Pennsylvania State College Center, Swarthmore, Pa.

#### **CORRECTION—HOUSTON MEETING**

Ralph Somers, an author of a student paper presented at the Houston meeting of A.I.Ch.E. is a student at Oklahoma A & M and not as stated on page 22 and page 45 of the April issue of C.E.P. from Texas A & M.



Crossville, Ill., plant of the Warren Petroleum Corporation. In the dehydration towers, the drying agent is Floridin Desiccant.

## **The Desiccant Used IS A FLORIDIN Product**

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# LOCAL SECTION NEWS

## PHILADELPHIA-WILMINGTON

The sixth and last meeting of the current season was held April 11 at the Clubhouse Hotel, Chester, Pa., with 103 at dinner and 135 at the meeting, to hear Alfred L. Baker, executive vice-president, Kellex Corp., New York, N. Y., on "Peacetime Utilization of Atomic Energy," and to present the awards in the Fred C. Zeisberg Memorial Contest.

Mr. Baker, assisted by T. Freear and C. K. Rainsford, demonstrated some potentialities in the field of nucleonics, particularly as they were viewed by an engineer interested in large-scale power production. A wide variety of other applications of radioactive isotopes was also included.

Awards in the Zeisberg contest, which was established by this section in 1941, are given for excellence in technical report writing to winners of a competition open to students in chemical engineering courses in any of eight schools in this locality: Bucknell, Drexel, Delaware, Lafayette, Lehigh, Pennsylvania, Princeton and Villanova. Chairman G. E. Holbrook requested Roy A. Kinckiner, Committee Chairman, to introduce the winners. They are George V. Vosseller, a June (1950) graduate of Lehigh University, first; Robert L. Richards, Jr., June (1950) graduate of University of Delaware, second; Louis C. Doelp, a June (1950) graduate of University of Pennsylvania, third. Each received books of his selection, appropriately marked.

At this meeting, after consideration of the request to Local Sections to suggest a nominee for Director of the

Institute, the section unanimously concurred with the recommendation of its committee in naming William T. Dixon, of The Atlantic Refining Co. and at present Chairman of the Institute Committee on Testing Techniques and Equipment Performance Standards.

The section met March 14 at Clubhouse Hotel with 77 at dinner and 115 at the meeting to hear Dr. Claude L. Benner, president of Continental American Life Insurance Co., on "Some Current Economic Trends."

Dean David L. Arm, University of Delaware, spoke briefly of the organization and aims of the Delaware Engineering Association.

*Reported by R. B. Chillas, Jr.*

## ST. LOUIS

At the meeting held March 22 at the York Hotel 90 members and guests were in attendance. Several student members from Washington University attended in response to the newly instituted program of inviting the junior, senior and graduate chemical engineering students to the meetings.

The speaker of the evening, Dr. Donald M. Calkins, assistant manager of the chemical engineering department of Merck & Co., gave his address on "Some Considerations in the Medicinal Chemicals Industry." From an economic standpoint the medicinal chemical field is essentially one of risk. It is a small volume producer in comparison with the heavy chemicals industry including multistep procedures with low over-all yields.

*Reported by R. S. Yates*

## F. C. ZEISBERG 1950 CONTEST WINNERS



G. V. VOSSELLER

R. L. RICHARDS, JR.

L. C. DOELP

## LOUISVILLE

This section was addressed April 19 by John H. Dobson on "Interconnected Pneumatic Instruments as Tools in Process Control." Mr. Dobson is manager for the chemical industries division of The Foxboro Co. and has had wide experience in design and operation of synthetic organic chemical plants and industrial waste disposal plants. He discussed pneumatic instrumentation applied to typical problems in chemical process control and showed how, by proper combination of several instruments, many specialized problems can be handled.

A committee known as "The Student Sponsorship and Professional Guidance Committee" has recently been set up to bring chemical engineering students in the Louisville area into closer contact with practicing engineers and with the Institute.

*Reported by W. B. Altsheler*

## PITTSBURGH

"Tools and Techniques of Process Engineering" were evaluated by Wayne C. Edmister, professor of chemical engineering, Carnegie Institute of Technology, in his address to the April 5 dinner meeting of this section at the College Club. The occasion was the annual "Junior Member Night," sponsored by the junior committee under the chairmanship of J. M. Harrison. Fifty-three members and guests were in attendance.

Professor Edmister demonstrated the interrelationships existing between design, development, and operation phases of research activities, as they affected the process engineer. A total of twelve time-tested tools and techniques available to the engineer was listed and explained.

*Reported by Hugh L. Kellner*

## KNOXVILLE-OAK RIDGE

At a meeting on March 28, 1950, in Oak Ridge, the guest speaker was Dr. Warren L. McCabe, President of the Institute. The subject of Dr. McCabe's remarks was "The Institute, Its Program and Problems." In addition to reviewing the purposes and organizational structure of the Institute, Dr. McCabe showed several slides which were prepared recently by the Public Relations Committee. The slides showed the Institute's membership and rate of growth during recent years, the number of chemical engineering graduates and accredited chemical engineering schools.

*Reported by W. B. Allred*

## NORTHERN CALIFORNIA

The meeting on March 6 was held in conjunction with the A.I.Ch.E. Student Chapter at the University of California in Berkeley, with a record attendance of 223 members, students, and guests.

The program was arranged by the Student Chapter under the direction of A. G. Dussik, president; J. H. Rogers, secretary; R. E. DeLaRue, treasurer; and P. J. Frederiksen, arrangements committee chairman. Tours were arranged through the chemical engineering laboratories, and through the supersonic wind tunnel of the mechanical engineering division. Brief talks on the development of the chemical engineering curriculum and research projects were given by Prof. T. Vermeulen, L. M. Grossman, and C. R. Wilke.

Among the research projects discussed and demonstrated were ion exchange, vapor-phase catalysis, vapor-liquid equilibrium studies, operating characteristics of plates and packed columns for distillation, absorption, and extraction, fundamental studies of diffusion and viscosity of multicomponent systems, convective film boiling, high-temperature calorimetry, thermal conductances at liquid-air temperatures, and electrochemical design studies. Related research in mechanical engineering, discussed at the meeting, included the flow properties of fluidized solids, two-phase liquid flow, evaporative cooling, and convective heat transfer.

The section met at the San Francisco Engineers' Club April 3 to hear a speech on "Labor's Part in the Free Enterprise System," by R. L. Condon, attorney for several labor organizations.

Approval was made of an annual award of a Junior membership in the National Society and local membership to the outstanding member of the University of California Student Chapter. The first award will be granted in June, 1950.

*Reported by R. H. Bunal  
and Theodore Vermeulen*

## NEW ORLEANS

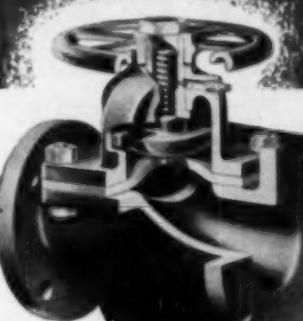
This section held a joint meeting with the Tulane Student Chapter March 16, 1950, in the Mechanical Engineering Building at Tulane University. In attendance were 63 members and guests.

A motion picture, "Jet Propulsion," was shown.

Highlight of the meeting was an address by Dr. Francis M. Taylor, head of Tulane's school of chemical engineering, on the history and development of the school. After this address groups were taken on a tour of the new unit operations laboratory.

*Reported by Ralph M. Persell*

**Now you can valve**  
**66° Be Sulphuric Acid**  
**without leakage, dripping**  
**or sticking**



**HILLS-MCCANNA**  
*Diaphragm Valves*  
with L-1  
**PLASTIC**  
**DIAPHRAGMS**

NEWLY developed plastic diaphragms for Hills-McCanna Diaphragm Valves now make it possible to handle 66° Be sulphuric acid without leaking, dripping or sticking. The combination of the proved Saunders Patent pinch clamp principle with the new plastic diaphragm puts an end to these troubles so common in valving 66° Be sulphuric.

Hills-McCanna Diaphragm Valves for handling 66° Be sulphuric are suitable for temperatures up to 125° F., pressures up to 100 psi. To get complete information, price and delivery data, write today. Specify valve sizes ( $\frac{1}{4}$ " to 4" incl.) and body material (cast iron, cast steel, Durimet or glass lined) desired. Full explanation of the Saunders Patent principle and specifications for Hills-McCanna valves for other services are given in Catalog V-48, available on request. **HILLS-MCCANNA COMPANY**, 2438 W. Nelson Street, Chicago 18, Illinois.

## **HILLS-MCCANNA** *diaphragm valves* **saunder's patent**

*Proportioning Pumps  
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## FUTURE MEETINGS AND SYMPOSIA OF A.I.Ch.E.

Chairman of the A.I.Ch.E. Program Committee

George E. Holbrook

Room 7406 Nemours Bldg.,  
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Wilmington, Del.

### SWAMPSCOTT MEETING PROGRAM MAY 28-31

(See March and April C.E.P.)

#### MEETINGS

**Regional** — Minneapolis, Minn., Radisson Hotel, Sept. 10-13, 1950.

**Technical Program Chairman:** E. L. Piret, Minnesota Mining & Mfg. Co., Minneapolis, Minn.

**Annual** — Columbus, Ohio, Neal House, Dec. 3-6, 1950.

**Technical Program Chairman:** John Clegg, Battelle Memorial Institute, Columbus, Ohio

**Regional** — White Sulphur Springs, W. Va., The Greenbrier, March 11-14, 1951.

**Technical Program Chairman:** Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.

**Regional** — Kansas City, Mo., Hotel Muehlebach, May 13-16, 1951.

**Technical Program Chairman:** Walter W. Dechner, J. F. Pritchard Co., Kansas City, Mo.

**Annual** — Atlantic City, N. J., Chalfonte-Haddon Hall Hotel, Dec. 2-5, 1951.

#### SYMPOSIA

**Indoor vs. Outdoor Plant Construction**

**Chairman:** J. R. Minevitch, E. B. Badger & Sons Co., 75 Pitts St., Boston, Mass.

**Meeting** — Minneapolis, Minn.

**Chemical Engineering Fundamentals**

**Chairman:** Mott Souders, Shell Development Co., 100 Bush St., San Francisco, Calif.

**Meeting** — Minneapolis, Minn.

**Chemical Engineering Kinetics**

**Chairman:** R. H. Wilhelm, Princeton (N.J.) University

**Meeting** — Minneapolis, Minn.

#### Chemical Engineering in Food Industries

**Chairman:** W. L. Faith, Corn Products Refining Co., Argo, Ill.

**Meeting** — Minneapolis, Minn.

#### Phase Equilibria

**Chairman:** W. C. Edmister, Carnegie Inst. of Tech., Pittsburgh, Pa.

**Meeting** — Minneapolis, Minn.

#### What Should You Know About Management?

**Chairman:** L. P. Scoville, Jefferson Chemical Co., 30 Rockefeller Plaza, New York, N. Y.

**Meeting** — Minneapolis, Minn.

#### Air and Water Pollution Control

**Chairman:** Richard D. Hoak, Mellon Institute of Industrial Research, University of Pittsburgh, Pittsburgh, Pa.

**Meeting** — Columbus, Ohio

#### Relationship Between Pilot-Scale and Commercial Chemical Engineering Equipment

**Chairman:** Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.

**Meeting** — White Sulphur Springs, W. Va.

#### Chemical Engineering in Glass Industry

**Chairman:** F. C. Flint, Hazel-Atlas Glass Co., Washington, Pa.

**Meeting** — Not scheduled.

#### Processing of Viscous Materials

**Chairman:** W. W. Kraft, The Lummus Co., 420 Lexington Ave., New York, N. Y.

**Meeting** — Not scheduled.

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, George E. Holbrook, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerp, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editor's office. Manuscripts not received 20 days before a meeting cannot be considered.

## EL DORADO CHEMICAL ENGINEERS' CLUB

At the monthly dinner meeting on March 17, the third since the club's formation, 89 technical men and guests gathered at Pan-Am Southern Corp.'s El Dorado Refinery Recreation Hall to hear W. D. Moore, a technical service engineer with the Reynolds Metal Co., discuss the "Applications of Aluminum to the Chemical and Petroleum Industries." Two sound films, one covering the operation of the Reynolds Co. from the mining of bauxite to the production of the finished metal, and the other the production of aluminum paint and its use as a protective coating, were shown during the meeting. The following morning members of the club were conducted on a tour through the ammonia synthesis plant of Lion Oil Co. and Pan-Am Southern Corp.'s refinery, both of which are located at El Dorado.

*Reported by E. D. Wurster*

## CHICAGO

The subject of modern industrial research and its present status drew an attendance of approximately 125 members at the March dinner meeting when Dr. Edward Weidlein, director of Mellon Institute of Industrial Research, and trustee of University of Pittsburgh, spoke on "Trends in Industrial Research." He presented a factual and vivid over-all appraisal of the position of all phases of research. Emphasis was placed on the need for divorcing immediate profit justification from many research programs in industry. The story of the development of many valuable processes and products was cited as proof of this necessity. Furthermore, the research personnel must be given more freedom of action in their pursuit of particular goals as an aid to better results.

*Reported by Donald A. Dahlstrom*

## OKLAHOMA

Approximately 80 members and guests attended the March 16 meeting at the McKinley School auditorium in Bartlesville.

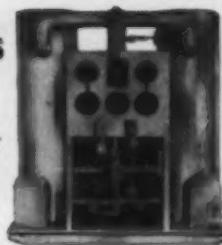
The Oklahoma Panhandle Counties of Cimarron, Tex., and Beaver were released to the Texas Panhandle Group for inclusion in its local Section, because of proximity.

Robert E. Fearon, nuclear physicist and director of research of Well Surveys, Inc., Tulsa, addressed the group on "The Hydrogen Bomb."

*Reported by George E. Hays*



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## LOCAL SECTION NEWS

(Continued from page 33)

### CHARLESTON, W. VA.

A general meeting of this section was held at the North Charleston Recreation Center on April 18, 1950; 130 members were present. The speaker was Howard Kehde, head of the Hypersorption division of the Foster Wheeler Corp.

Mr. Kehde presented up-to-date information on the Hypersorption process, the relatively new chemical engineering technique for removing or recovering troublesome or valuable constituents present in gases in such low concentration that other separation methods are not economically feasible. He described the functions of the four commercial hypersorbers which Foster Wheeler Corp. has designed.

During the business meeting the nominating committee chairman, Dr. R. L. Sibley, proposed the following candidates for the 1950 annual election:

Chairman..... A. B. Stiles—Du Pont  
Vice Chairman..... J. R. Durland—Monsanto  
D. J. Porter—Westvaco

Secretary... G. B. Bradshaw, Jr.—Du Pont

M. C. Guthrie, Jr.—Du Pont

Treasurer..... K. J. Gutshaw—Carbide

J. H. Howell—Carbide

Member-at-large of Executive Committee:

J. W. Conwell—Viscose

C. C. Richiusa—Monsanto

Reported by R. W. King

### OHIO VALLEY

Members and guests of this section made an inspection trip through the distillery of Jos. E. Seagrams Sons, Inc., Lawrenceburg, Ind., on April 1. Prior to the inspection trip the group was shown Seagrams' film on the "Manufacture of Whiskey." The C. F. Braun Co., of Alhambra, Calif., also presented a film showing "Action in Bubble Cap Columns."

Reported by A. C. Greber

### TENNESSEE VALLEY

Dr. L. K. Herndon, director of research of the Matheson Chemical Corp., was the speaker at the April 3 meeting of this section at Wilson Dam. His subject was "The Recovery of Sulfur from Sour Natural Gases."

Dr. Herndon pointed out that many natural gases contain sulfur in the form of  $H_2S$  in objectionable amounts. The usual way to remove the  $H_2S$  is to scrub it from the natural gas, convert the  $H_2S$  to  $SO_2$ , and discharge the  $SO_2$  to the atmosphere. Because the discharge of  $SO_2$  to the atmosphere is undesirable in many areas, the former Southern Acid and Alkali Corp. requested the Research Foundation at Ohio State to develop a process for converting  $H_2S$  to elemental sulfur. With the use of well-prepared

slides, Dr. Herndon traced the development of this process by the Research Foundation through the laboratory stage and pilot plant work to the erection of a successful commercial size unit. In certain areas sulfur produced by this process competes in price with that obtained by the Frasch process, Dr. Herndon stated.

Reported by Gordon Stoltz

### SOUTHERN CALIFORNIA

The April dinner meeting of this section was held in Carl's Viewpark Restaurant, Los Angeles. Some 70 members and guests were in attendance.

Dr. John H. Ballard, assistant professor of chemical engineering, University of Southern California, presented a paper on "Limiting Flow Phenomena in Packed Liquid-Liquid Extraction Columns." Dr. Ballard's talk covered the results of an experimental investigation on a 3½-in. liquid-liquid extraction column packed with Rasching rings. Water was used as one phase, either continuous or dispersed, and a number of fluid mixtures with widely varying physical properties as the other phase. Of interest in this respect was the inclusion of solvents with specific gravities higher than that of water. A transition point, rather than the usual flooding point, was defined for the various systems.

Reported by William J. Baral

### NEW JERSEY

E. V. Murphree, president, Standard Oil Development Co., was the guest speaker at the March 14 meeting before 100 members at the Hotel Winfield Scott in Elizabeth. His talk was titled "The Process Development and Properties of Butyl Rubber."

Reported by D. A. Levenson

### AKRON

D. M. Considine, manager, market extension division, Brown Instrument Co., spoke to 50 members and guests at the University Club.

Mr. Considine stated that smaller chemical plants have tended to neglect instruments for controlling processes. In contrast to this, large plants use instruments widely with a trend towards robotization.

"At this meeting the film, "Atomic Energy and Advanced Physics" was shown.

Reported by J. W. Kosko

### TWIN CITIES

At the May meeting of this section held at Freddie's Cafe, Minneapolis, May 11, 1950, Dean Athelstan Spilhaus of the Institute of Technology, University of Minnesota, spoke on his Arctic research.

Reported by W. M. Podas

# PERSONALIA

A.I.Ch.E. MEMBERS HONORED BY MONSANTO



R. E. COLWELL



F. LABELLE

Robert E. Colwell and Frank LaBelle were among the four scientists named by Monsanto Chemical Co. to receive leaves of absence at full salary for an academic year of study at universities of their choice.

Mr. Colwell joined the research department of Monsanto's plastics division at Springfield, Mass., in November, 1945. His work has been principally in the field of spray-drying problems. He was graduated from Rhode Island State College in 1943 with a B.S. degree in chemistry. Prior to joining Monsanto he served in the U. S. Navy for two years.

Mr. LaBelle is chief chemical engineer of the phosphate division's engineering department at Anniston, Ala. He was graduated from Michigan State College in 1941 with a B.S. in chemical engineering. He has served as analytical chemist, chemical engineer, chemical design engineer, and assistant chief engineer since joining the department.

The plan is designed to encourage the scientific work and further development of Monsanto's technical personnel in physics, chemistry and chemical engineering. The aim of the program is to establish close cooperation between industry and the university laboratories. The leaves are awarded on the basis of outstanding performance.

## HASLAM NOT NOMINEE JERSEY STANDARD BOARD

Robert T. Haslam, a vice-president and a director of Standard Oil Co. (New Jersey), who plans to retire in the fall, has asked not to be a nominee for reelection as a director at the company's annual meeting to be held June 7. Until retirement Mr. Haslam will continue as a vice-president of the company. Mr. Haslam's career in the oil business has ranged from research to sales and public relations.

Graduated in 1911 from the Massachusetts Institute of Technology he remained as assistant instructor in analytical chemistry before joining the National Carbon Co., Cleveland, where he was consecutively research chemist, production engineer and assistant superintendent. In 1920 he returned to MIT as assistant professor and head of the school of chemical engineering practice and for five years directed the research laboratory of applied chemistry. At that time he also inaugurated the course in gas and fuel engineering.

During this period, Mr. Haslam served on occasion as consultant to the

Standard Oil Development Co., central research organization of Standard Oil Co. (New Jersey) affiliates. In 1927 he accepted an offer to become a member of the board of directors of the Standard Oil Development Co.; in 1933 he was made coordinator of the lubrication sales department; in 1942 he became a director, Standard Oil Co. (New Jersey), and in 1945 he was elected a vice-president.

In collaboration with R. P. Russell, he is author of "Fuels and Their Combustion," and coauthor of "Britain's Fuel Problems."

Sam Tour, chairman of the board of Sam Tour & Co., Inc., of New York, N. Y., president of The American Standards Testing Bureau, Inc., of the Forty Four Trinity Place Corp., and of Graphitized Alloys Corp., also of New York, has recently been elected chairman of the Inter Society Corrosion Committee of the National Association of Corrosion Engineers. He began his corrosion studies during World War I while employed by the Ordnance Department of the U. S. Army.



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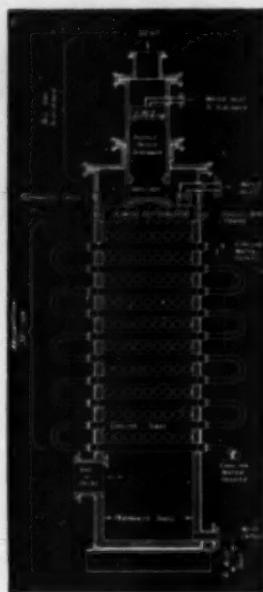
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## PERSONALIA

(Continued from page 35)

### PARTRIDGE SUCCEEDS HALL AS DIR. HALL LABS.

Everett P. Partridge, who has been director of research for Hall Laboratories, another Hagan subsidiary, Calgon, Inc., for many years, will assume active direction of Hall Laboratories, Inc., Pittsburgh, Pa. This promotion is occasioned by Ralph E. Hall's recent announcement of his relinquishment of active direction. Dr. Hall has served as director of Hall Laboratories, Inc., since it was founded by Hagan Corp., Pittsburgh combustion and chemical engineering firm, on April 1, 1925.

Dr. Partridge began his career as associate editor of *Industrial and Engineering Chemistry* and subsequently became part-time research engineer, department of engineering research, University of Michigan, and still later was affiliated with the U. S. Bureau of Mines as supervising engineer directing chemical research and process development at Nonmetallic Minerals Experiment Station.

Dr. Hall, known as an authority on industrial and municipal water-conditioning, will continue his scientific work as consultant with the firm and remain a member of the board of directors. He holds the Modern Pioneer Award given by the National Association of Manufacturers, and the first Pittsburgh Award for Outstanding Service given by the ACS, Pittsburgh section.

Louis M. Levy, a chemical engineer with the Mound Laboratory of Monsanto Chemical Co. in Miamisburg, Ohio, has been appointed visiting professor of chemical engineering at the University of Antioquia, Medellin, Colombia, S. A. The appointment was arranged through the State Department as part of the United States Govern-

E. P. PARTRIDGE



ment's cultural exchange program. Mr. Levy, who has been with the Mound Laboratory since 1947, received a B.A. degree in chemistry from Brooklyn College in 1941 and after serving two years in the Army as sergeant in the 84th Infantry Division he received a degree of Bachelor of chemical engineering at the Polytechnic Institute of Brooklyn in 1947.

### NICKOLLS ACTING HEAD CHEM. ENG. OKLA. A & M

Charles L. Nickolls was recently appointed acting head of the school of chemical engineering at Oklahoma A. & M. College, Stillwater, Okla., where he has been a teacher in chemical engineering and also for the last ten years assistant chairman of the department.

Dr. Nickolls served in World War I and in World War II was in civil service as civilian educational advisor. For three years he was chemical engineer and advisor for the National Dyers and Cleaners Association of America. In 1928-29 he was the recipient of a Research Fellowship for the Natural Gasoline Manufacturers of America in which he worked on gasoline volatility. At times, he has been engaged in various investigations in a consulting capacity. His interest in natural gasoline put him in the employ of Phillips Petroleum Co. in connection with the manufacture of natural gasoline.

He was graduated from Dakota Wesleyan University with a B.S. degree in 1917, and received the M.S. degree from Oklahoma A. & M. College in 1921. He studied chemical engineering at Columbia University and the University of Michigan and in 1935 received a Ph.D. degree in chemical engineering from the University of Michigan.

Dr. Nickolls' interests are in the fields of heat transfer, absorption distillation, catalysis, internal combustion engines, combustion, petrography, and micro-crystalline waxes.

C. L. NICKOLLS



O. M. SMITH



Dr. Otto M. Smith has been appointed full-time director of the Research Foundation at Oklahoma A. and M. College, Stillwater, Okla. This organization supervises research projects for both private and governmental organizations, and assists staff members in their own research work.

Dr. Smith recently retired as head of the departments of chemistry and chemical engineering after serving 26 years at Oklahoma A. and M. College and was given an emeritus standing. He is replaced by Dr. Charles Nickolls as the acting head of the department of chemical engineering. (See page 36.)

Earl Engler recently joined the Girdler Corp. and was assigned to the operating department. A graduate of Notre Dame University, Mr. Engler was formerly with the Monsanto Chemical Co., at Dayton, Ohio.

#### HULME OPENS OWN CONSULTING OFFICE

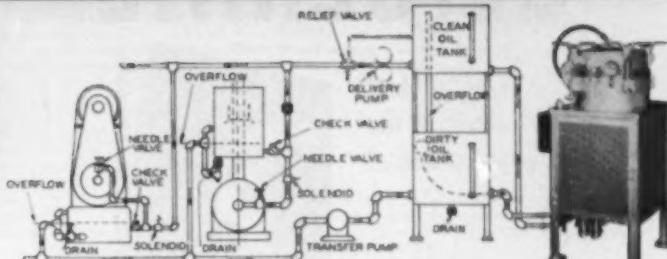
Richard E. Hulme, formerly with the development department of Diamond Alkali Co., at Painesville, Ohio, has resigned his position to open a consulting office in Bradford, Pa. He and his associates will specialize in problems dealing with the heavy chemical, petrochemical, petroleum and the process industries in both the design and economic evaluation phases.

In the six years he was associated with Diamond Alkali he developed a magnesium oxide process, a method of dehydrating caustic soda, and a method of recovering liquid chlorine from purge gas.

During the war Mr. Hulme was employed as a process design engineer with Blaw-Knox Co., at Pittsburgh, and was a member of the engineering team responsible for the basic design of the copolymer synthetic rubber plants.

Previously he had been associated with the Kendall Refining Co., as assistant chief engineer at its refinery at Bradford.

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## PERSONALIA

(Continued from page 37)

### D. F. SMITH GOES TO MICHIGAN STATE

Dr. David F. Smith, vice-president and director of research, Johnson and Johnson Co., New Brunswick, N. J., was appointed head of the department of chemical engineering at Michigan State College, East Lansing, Mich., effective April 16. Fifty-three years old, Dr. Smith has held many research and executive positions in industry and government. He was chief of the Motor Fuels Division, U. S. Department of Agriculture, from 1939-40; chief engineer in charge of process research and development, Michigan Alkali Co., from 1940-42. He has also held positions with the U. S. Bureau of Mines, Hooker Electrochemical Co., and the Hercules Powder Co.

Once a student of Albert Einstein at the University of California, Dr. Smith has 14 years' experience in teaching and research at the California Institute of Technology, University of California, and Buffalo University. He received his B.S. and Ph.D. degrees from the California Institute of Technology in 1920 and 1922, respectively.

Dr. Smith was long engaged on the theory of solutions, and is the author of 28 scientific papers published in technical journals of U. S. and Germany. He is also the author of the solubility chapters in Volume 3 of the International Critical Tables.

### RAIMOND, MUNRO IN CALCO APPOINTMENTS

Appointments were announced recently by American Cyanamid Co.'s Calco chemical division.

Dr. W. A. Raimond was appointed departmental technical director for dyes and Dr. W. P. Munro chief chemist department G of dyes manufacturing division.

Dr. Raimond is a graduate of Rhode Island State College, with a B.S. in chemistry. He obtained his Master's and Doctor's degrees from Rutgers University where he later worked as a graduate assistant in chemistry.

Dr. Munro is a graduate of the University of Iowa with a B.S. and M.S. in chemical engineering. He obtained his Doctor's degree in chemistry from Princeton University. Dr. Munro was appointed a Du Pont Company Fellow at Princeton (1932-33) and later joined the Calco organization. Dr. Munro served as an officer in the Chemical Warfare Service, Technical Command, Edgewood Arsenal, Md., in charge of smoke munitions (1942-45).

(Personalia continued on page 40)

## CLASSIFIED SECTION

Advertisements in the Classified Section of Chemical Engineering Progress are payable in advance, and are placed at 15¢ a word, with a minimum of four lines accepted. Box number counts as two words. Advertisements average about six words a line. Members of the American Institute of Chemical Engineers in good standing are allowed one six-line insertion free of charge per year. More than one insertion to members will be made at half rates. In using the Classified Section of Chemical Engineering Progress it is agreed by prospective employers and employees that all communications will be acknowledged, and the service is made available on that condition. Boxed advertisements one-inch deep are available at \$15 an insertion. Size of type may be specified by advertiser. In answering advertisements all box numbers should be addressed care of Chemical Engineering Progress, Classified Section, 120 East 41st Street, New York 17, N. Y. Telephone ORagon 9-1360. Advertisements for this section should be in the editorial offices the 25th of the month preceding the issue in which it is to appear.

### SITUATIONS OPEN

**Sales Engineers**—Graduate, with minimum of five years' sales experience, to sell heavy equipment. Age 30 to 40 preferred. Send resume of educational and business history to Box 5-5.

### SITUATIONS WANTED

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**University Teaching and Research**—Position in chemical engineering. Purdue, B.S.Ch.E., 1942; Michigan, M.S., 1943; Ph.D., June, 1950. Two years' industrial experience, four years teaching. Fellowships, so-cities. Age 29; married. Box 1-5.

**Supervisory Chemical Engineer**—B.S., 31. Experienced in supervision, operations, pilot plant development, plant design, and economic studies of petroleum and petrochemical plants. Desire responsible engineering position with small company. Box 2-5.

**Industrial Research Group Leader**—Registered engineer. Twenty-two years' experience in guiding new projects from conception through final plant demonstration. Would prefer organizing permanent research group for medium size company. Box 3-5.

**Executive Engineer**—Chemical engineer engaged in direction of group designing plants for soaps, detergents, chemicals, and pharmaceuticals. Seek position as chief engineer. In present position have overall responsibility for projects. Metropolitan area preferred. Box 4-5.

**Chemical Engineer**—B.S., 1948. Two years' extensive experience in development organic chemicals. Desire position in large eastern company. Particularly interested in process control work. Box 6-5.

**Chemical Engineer**—B.Ch.E., 1948. M.Ch.E. 1949; single, 23. Two years' Chemical Welfare Service laboratory supervisory work. One year industrial experience. One year teaching chemistry. Willing to travel. Location immaterial. Excellent academic record and references. Box 7-5.

**Management Engineer**—Ability as analyst and investigator; cleaning up trouble spots. Ch.E. background. B.S.M.S. Interested in work as executive assistant or in similar capacity. Can double as company pilot. Box 8-5.

**Chemical Engineer**—B.Ch.E., 1939, family, 53. Eight years' supervisory development experience on petroleum and petro-chemical

pilot plants, and 2½ years on industrial chemical plants. Desire responsible position requiring technical, administrative, and organizational ability. Box 10-5.

**Chemical Engineer**—M.Ch.E., Prof. Eng. (N.Y.), 28, single, 4½ years' diversified engineering experience. 3 years of college teaching. 1½ years of law school completed. Desire position in patent law office in New York City area with opportunity to finish law school evenings. Box 12-5.

**Chemical Engineer**—D.Eng., Yale 1950, S.M. M.I.T. 1948, age 25. Honorary societies, highest grades. Desire permanent position in process design or economics or development in New England or Middle Atlantic region. Available summer 1950. Box 13-5.

**Chemical Engineer**—M.Ch.E., June 1950, Univ. of Louisville. Family, 28. Phi Kappa Phi, Sigma Tau. Bomber pilot in last war. Desire process development, design work, or administrative position where technical knowledge is required. Box 14-5.

**Chemical Engineer**—B.S. and M.S., age 29, married. Three years in refinery process engineering group of major oil company; two years research and development organic chemicals. An extrovert; desire position in sales, production, etc., where background would be an advantage. Prefer South or Southwest location. Box 15-5.

**Industrial Chemical Engineer**—Good educational background. Twenty years' experience superintendent production-maintenance-construction, processing ores, brines, gases and recoveries. Supt. large development dept.; electrochemical operations; physical chemical research; chlorination processes; cost estimating. Prefer production; development supervision. Box 16-5.

#### Nonmembers

**Young Man**—B.Ch.E., Clarkson College of Tech. Desire position production, process development or research. Salary secondary to opportunity. Box 9-5.

**Design Engineer**—B.S.Ch.E., 1936. Three years' chemical research experience. Eight years group leader research, development, design mechanical components. Desire position with firm developing and designing chemical equipment and processes. Outstanding record. Box 17-5.

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## PERSONALIA

(Continued from page 38)

**Ferdinand B. Zienty** was recently appointed associate director of the St. Louis research department of the organic chemicals division of Monsanto Chemical Co. Dr. Zienty, who has been with the St. Louis research department since 1938 when he was employed as a research chemist, is a native of Chicago. He received his Ph.D. degree from the University of Michigan in 1938. The author of numerous articles and patents, Dr. Zienty was appointed research group leader in 1940 and assistant director in 1947. He is a member of several technical societies.

### J. N. TILLEY IN NEW DU PONT ASSIGNMENT

John N. Tilley, departmental engineer of the Du Pont Co.'s Grasselli chemicals department, has been appointed manager of the new division known as the planning division in the company's rayon department. Mr. Tilley started with the Du Pont Co. in 1928 as a chemist in the Eastern Laboratory, Gibbstown, N. J. He has done special work for the company in South Africa and Great Britain. During the war, he was associated with the Du Pont division which operated the Hanford (Wash.) plant in the government's atomic energy project.

Mr. Tilley was born in 1905 in Everett, Wash., and was graduated from the University of Washington in 1928 with a B.S. degree in industrial chemistry.

The planning division will assist the general management of the rayon department in charting the manufacturing and merchandising phases of its business. Manufacturing operations of the rayon department are centered in the acetate division, nylon division and rayon division.

### R. H. BLANCHARD NOW PRESIDENT OF HOOD

Raymond H. Blanchard was recently elected president of the Hood Rubber Co., Watertown, Mass., a division of the B. F. Goodrich Co.

After graduating from Massachusetts Institute of Technology Mr. Blanchard joined the Hood organization in 1917. He directed the mixing and reclaiming departments. He became factory manager in 1927, production superintendent the following year and in 1932 was elected vice-president in charge of all company manufacturing.

He is a veteran of World War I and during World War II was a member of the Greater Boston War Manpower Commission. He is the fourth president of the pioneer New England rubber company.

**Neal Truslow** has been appointed supervisor of product development for United States Rubber Co.'s textile division development department. He will have his headquarters at the company's new textile research laboratories in Winnsboro, S. C. He will be responsible for the textile division's new product development other than Asbeston, and his duties will also include the direction of the chemical laboratory at Winnsboro. Mr. Truslow is a graduate of Johns Hopkins University in chemical engineering and was formerly with Chicopee Manufacturing Corp., where he was engaged in textile research. He is a native of Chestertown, Md.

**H. Zeh Hurlburt** has accepted a position as research engineer for Consolidated Chemical Industries, Inc., at its Houston (Tex.) plant. There he will be engaged in new product research. He received the Sc.D. in chemical engineering from Massachusetts Institute of Technology in January, 1950.

**E. R. Beecher**, formerly project engineer, central engineering division, Colgate-Palmolive-Peet Co., Jersey City, N. J., is now head of project engineering and construction, central engineering division of the same company. He remains in Jersey City, N. J.

**Douglas M. Considine** has been appointed manager of the market extension division, general sales, Brown Instruments division, Minneapolis-Honeywell Regulator Co. Mr. Considine's new duties will include direction of advertising and technical and trade editorial activities. He will continue as technical editor of *Instrumentation*, Brown's house-trade publication. Mr. Considine is a graduate of Case Institute of Technology and holds a Bachelor's degree in chemical engineering. He has been with the company since 1941.

## Necrology

### MERLE RANDALL

Merle Randall, research director, research laboratory, Randall & Son, Berkeley 4, Calif., died recently. He was previously associated with the Stuart Oxygen Co., Berkeley, and prior to that was professor of chemistry at the University of California. Dr. Randall received his A.B. from the University of Missouri (1907), his A.M. from the same university (1909), and a Ph.D. from Massachusetts Institute of Technology (1912). He was 62 years old.

### B. G. NELSON

B. G. Nelson, of the Thiokol Corp., Huntsville, Ala., died recently. Prior to his employment with the Thiokol Corp. he was with the Air Reduction Co.



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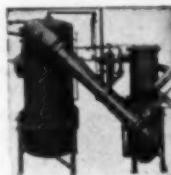
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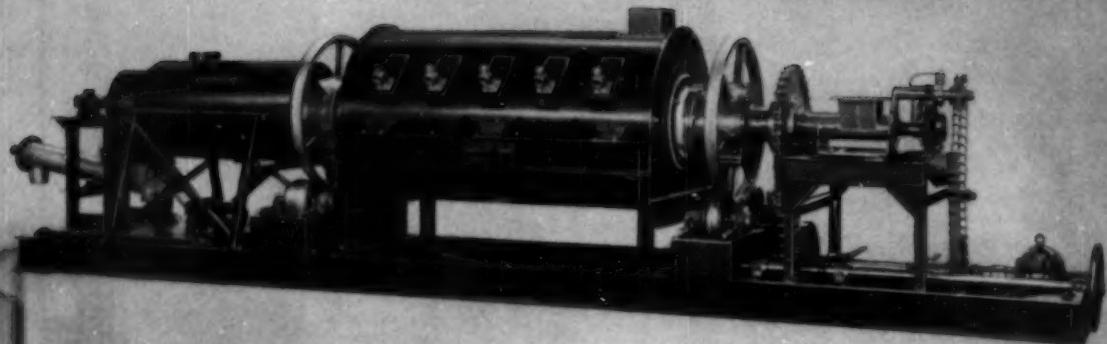
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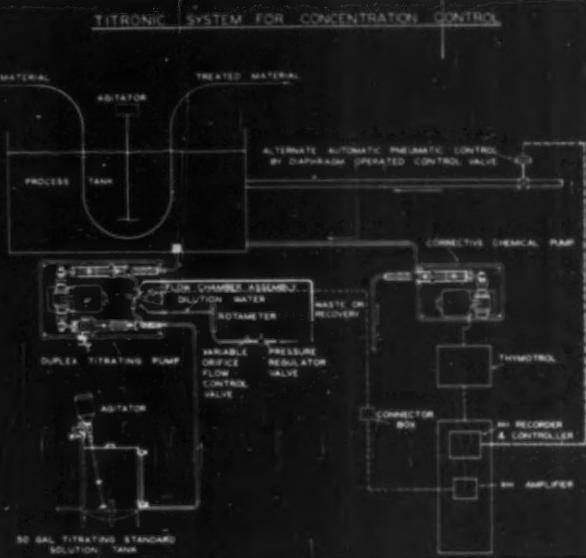
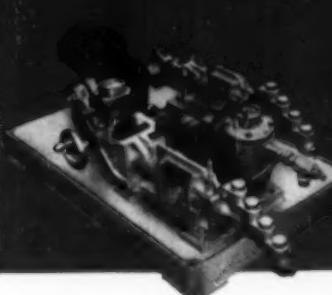
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